



~~DUE TWO WEEKS FROM LAST DATE~~

APR 29 1957.

AUG 9 1957

GPO 16-71341-1



In: Handb. Radioact. (Siri, W.)  
Dayton, 1948,



Report No. 5669

Date 13 February 1948

INDEXED

APR 28 1950

(DEPARTMENT OF THE AIR FORCE)  
U.S. Air Force. AIR MATERIEL COMMAND  
Dayton, Ohio

AF TECHNICAL REPORT

NO. 5669

HANDBOOK OF RADIOACTIVITY AND TRACER

METHODOLOGY

Title

By

WILLIAM SIRI  
Division of Medical Physics  
University of California

with contributions

by

ELLSWORTH C. DOUGHERTY  
Research Fellow in Medical Physics

CORNELIUS A. TOBIAS  
Assistant Professor of Medical Physics

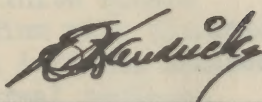
RAYBURN W. DUNN

PATRICIA R. WEYMOUTH  
Research Fellow in Medical Physics

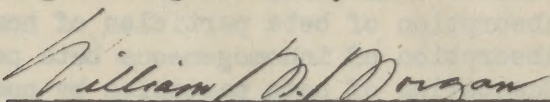
JAMES S. ROBERTSON

MAURICE C. FISHLER

APPROVED:

  
EDWARD J. KENDRICKS, Col. MC  
Chief, Aero Medical Laboratory  
Engineering Division, AMC

APPROVED:

  
WILLIAM M. MORGAN, Brig. Gen., USAF  
Chief, Engineering Division Operations  
Air Materiel Command

Laboratory No. MCREXD  
E.O. No. 696-60  
No. of Pages 867  
No. of Figures 117  
No. of Tables 27



# TABLE OF CONTENTS

Page

## ACKNOWLEDGEMENT

9

## SUMMARY

11

## I. NUCLEI AND RADIOACTIVITY . . . . . 13

### 1. Physical constants . . . . . 13

### 2. Radioactivity Units . . . . . 15

### 3. Properties of Nuclei . . . . . 21

- A. Stable isotopes
- B. Mass defect
- C. Packing fraction
- D. Binding energy
- E. Nuclear spin
- F. Magnetic diopole
- G. Electric quadrupole moment

### 4. Gamma Rays . . . . . 71

- A. Properties
- B. Photoelectric effect
- C. Scattering of gamma rays
- D. Pair production
- E. Secondary particle production
- F. Internal conversion

### 5. Beta Particles . . . . . 90

- A. Physical properties
- B. Absorption processes
- C. Ionization
- D. Specific ionization
- E. Radiative losses
- F. Nuclear excitation
- G. Absorption of beta particles of homogenous energy
- H. Absorption of inhomogeneous beta particle beams
- I. Scattering of beta particles by nuclei
- J. Scattering by electrons
- K. Beta decay
- L. Selection rules for beta decay
- M. K - capture

### 6. Alpha Particle . . . . . 121

- A. Physical properties
- B. Absorption of alpha particles
- C. Average ionization potential



# TABLE OF CONTENTS (cont'd)

D. Correction terms	
E. Relative stopping power	
F. Atomic stopping power	
G. Mass stopping power	
H. Range of particles	
I. Specific ionization	
J. Delta rays	
K. Straggling of alpha particles	
L. Scattering of alpha particles	
M. Alpha decay	
7. Protons . . . . .	152
8. Deuteron . . . . .	185
9. Neutrons . . . . .	189
A. General properties	
B. Elastic scattering of neutrons	
C. Interaction of slow neutrons with nuclei	
D. Interaction of fast neutrons with nuclei	
E. Reflection of slow neutrons	
F. Diffraction of neutrons	
G. Laue - Bragg reflection	
H. Reflection and refraction	
10. Neutron Diffusion . . . . .	218
A. Diffusion equation	
B. Point source in infinite medium	
C. Plane source in infinite medium	
D. Point source in long column	
E. Finite source in infinite medium	
F. Point source in finite sphere	
G. Semi-infinite medium with plane boundary	
H. Absorbing foil in infinite medium with point source	
I. Production of thermal neutrons	
J. Point source of fast neutrons	
11. Radioactivity . . . . .	250
12. Radioactive Decay . . . . .	366
A. Law of radioactive decay	
B. Fluctuations	
C. Simple decay	
D. Growth of radioactivity	
E. Radioactive substance produced by parent of long half life	
F. Parent and daughter of comparable half life	
G. Decay of nth component in radioactive chain	

422651



# TABLE OF CONTENTS (cont'd)

Page

13. Fission . . . . .	373
A. Mechanism of fission	
B. Fission probability	
C. Stability of heavy nuclei	
D. Energy relations	
E. Fission products	
14. Electrostatic Generator . . . . .	391
15. Betatron . . . . .	396
A. Description	
B. Electron injection and beam extraction	
C. Orbital oscillations	
D. Focusing	
16. Synchrotron . . . . .	402
A. Description	
B. Motion of particles	
C. Energy loss by radiation	
D. Synchrotron operation	
17. Cyclotron. . . . .	412
A. Description	
B. Ion paths	
C. Ion source	
D. Cyclotron targets	
E. Synchro-cyclotron	
II. MEASUREMENT OF ISOTOPES . . . . .	433
18. Geiger Counters . . . . .	433
A. General properties	
B. Non-self quenching counters	
C. Self-quenching counters	
D. Pulse and voltage characteristics	
E. Filling gases	
F. Counting tube life	
G. Gas counters	
H. H 3 gas counters	
I. C 14 gas counter	
J. Neutron counters	
K. Slow neutron counters	
L. Fast neutron counters	
M. Accuracy of counting measurements	
N. Average deviation	
O. Standard deviation	



## TABLE OF CONTENTS (cont'd)

Page

P.	Probable error	
Q.	High counting rate losses	
R.	Counter revolving time	
S.	Coincidence counting rate	
T.	Counting rate meter	
19.	Proportional Counters . . . . .	469
A.	General features and use	
B.	Theory of operation	
20.	Standardization of Radioactive Samples . . . . .	473
A.	Introduction	
B.	Units of radioactivity	
C.	General methods	
D.	Primary alpha particle standards	
E.	Beta particle standards	
F.	The uranium standard	
G.	RaD and RaE standard	
H.	The coincidence method	
I.	Gamma ray standards	
J.	Geometrical efficiency	
K.	Extended thin samples	
L.	Thick samples	
M.	Comparison between different methods	
21.	Ionization Chamber . . . . .	497
A.	Description	
B.	Statistics of measurements	
22.	Indirect methods for measuring stable isotopes . . . . .	506
A.	Introduction	
B.	Preparation and purification of water	
C.	Refractive index	
D.	Pycnometer	
E.	Submerged float	
F.	Falling drop	
G.	Diffusion gradient	
23.	Mass Spectrograph . . . . .	515
A.	Aston mass spectrograph	
B.	Dempster mass spectrograph	
C.	Mattauch double focusing spectrograph	
D.	Bainbridge - Jourdan double focusing mass spectrograph	



## TABLE OF CONTENTS (cont'd)

E.	Trochoidal trajectory mass spectroscope	
F.	Ion sources	
G.	Detector requirements	
H.	Photographic plates	
I.	Electrical devices	
24.	Treatment of Biological Tissue for Recovery of Radioactive Elements . . . . .	537
A.	Dry ashing	
B.	Wet ashing	
25.	The Preparation of Thin Films of Radioactive Elements by Electrolysis . . . . .	548
A.	General considerations	
B.	Electroplating	
C.	Apparatus	
D.	Anodes	
E.	Cathodes	
F.	Electrodeposition	
G.	The electrolysis current and voltage	
26.	Iron Determination. Electroplating and Analysis . . . . .	560
A.	Electroplating	
B.	Iron Analysis	
27.	The Recovery and Estimation of Gold . . . . .	564
A.	Procedure	
B.	Notes on the analytical procedure	
28.	The Electrodeposition of Uranium. . . . .	570
29.	Radioautography . . . . .	575
30.	Manufacturers of Isotope Measuring Instruments . . . . .	580
III.	BIOLOGICAL AND MEDICAL APPLICATION OF ISOTOPES . . . . .	583
31.	Introduction . . . . .	583
32.	General Critique of the Biological Application of Isotopes. .	584
A.	Introduction	
B.	Survey of useful isotopes	
C.	Isotopes as tracers	
D.	Differential behavior and effects of isotopes	
33.	Elements Constituting Major Organic Metabolites . . . . .	614
A.	Introduction	
B.	Carbon	
C.	Hydrogen	



## TABLE OF CONTENTS (cont'd)

D.	Oxygen	
E.	Nitrogen	
F.	Sulphur	
G.	Phosphorus	
34.	Elements Constituting Major Mineral Metabolites. . . . .	623
A.	Introduction	
B.	Sodium	
C.	Potassium	
D.	Calcium	
E.	Magnesium	
F.	Chlorine	
35.	Trace Elements Known to be Essential in Animals and Plants . . .	629
A.	Introduction	
B.	Iron	
C.	Iodine	
D.	Manganese	
E.	Copper	
F.	Zinc	
G.	Cobalt	
H.	Boron	
I.	Aluminum	
J.	Silicon	
K.	Molybdenum	
L.	Vanadium	
36.	Elements not Known to be Essential to Life . . . . .	639
A.	Introduction	
B.	Possible micronutrient elements	
C.	Elements of importance in pharmacology and toxicology	
D.	Noble gases	
E.	Rare earth elements (lanthanide series) and other elements in fission	
F.	New rare earth elements (actinide series)	
G.	Other elements	
37.	Isotopes in Therapy and Diagnosis . . . . .	649
A.	Introduction	
B.	Radiophosphorus	
C.	Radioiodine	
D.	Other isotopes	
38.	Biological Effects of the Natural Radioactive Elements . . . . .	661
A.	Introduction	
B.	Organic substances	



TABLE OF CONTENTS (cont'd)

Page

D. Plants

E. Mammals

IV. BIBLIOGRAPHY OF STABLE AND RADIOACTIVE TRACERS APPLIED TO BIOLOGY AND MEDICINE . . . . .	673
---	-----

INDEX OF TABLES



## ACKNOWLEDGMENTS

The need for a handbook of radioactivity and tracer methodology was early recognized by Lt. Colonel A. P. Gagge, MSC, of the Aero Medical Laboratory, Engineering Division, Air Materiel Command, Wright Field, and at his suggestion the present handbook was compiled under contract No. W33-038-ac-14792, between the Air Forces and the University of California. From the beginning, through to its completion, the project has had the active interest and assistance of Dr. John H. Lawrence to whom the authors owe a great debt of gratitude.

The sections of the handbook written and compiled by the contributing authors are listed below:

Ellsworth C. Dougherty -	Sections 31 to 37 inclusive; bibliography, Part IV (with M. C. Fishler).
Rayburn W. Dunn -	Sections 24 to 28 inclusive.
Cornelius A. Tobias -	Section 20.
Patricia P. Weymouth -	Sections 29 and 38.
James S. Robertson -	Section 22.
Maurice C. Fishler -	Bibliography, Part IV (with E. C. Dougherty).

A considerable portion of the labor in preparing the manuscript was borne by Mr. Ellis H. Myers for whose skill in preparing the diagrams and graphs we are exceedingly grateful, and by Mrs. Janet Dwight and Miss Jean Smith for whose patience and fortitude in typing the manuscript we are deeply appreciative.

We wish also to acknowledge our indebtedness to Professor Robert Serber for his generous permission to use the range-energy data calculated by B. G. Hoffman and Walter Aron of the Radiation Laboratory, University of California, and to Professor Robley D. Evans for his permission to reproduce the graphs



# ACKNOWLEDGMENTS (cont'd)

of gamma ray absorption coefficients and neutron cross sections. None of these data have been previously published.

We wish finally to make our acknowledgment to the Atomic Energy Commission for their generous assistance on this project.

William Siri

Berkeley, California

November 1947



## GENERAL SUMMARY

The recent very rapid developments in nuclear physics and the parallel progress in tracer methodology have made it imperative to compile from the vast accumulation of data and experimental procedures that information which appears to be the most reliable as well as essential to the application of tracer technics. For the most part, such information is to be found at the present time only in a widely scattered literature. Nuclear physicists, to be sure, have access to this information by virtue of their familiarity with the technical literature in the field, but even for the nuclear physicist, it is usually necessary to refer to many different sources for the explicit data he requires. The situation is very much worse for those who are less familiar with nuclear physics, but who plan to employ stable or radioactive isotopic tracers and high energy radiations in their research. For such persons, Seaborg's "Table of Isotopes" has been literally the only comprehensive source for some of the essential information.

Until recently, the compilation of a handbook would have been somewhat futile, since there was too little data that was firmly established and a compilation once made, would have had to be completely revised and considerably extended six months later. Now, however, it is felt that at least an effort can be made in this direction with the accumulated information derived from the extensive research during and since the war, and particularly, because the demand for this information in fields other than nuclear physics has increased enormously. The experimental data and technics are still in a state of flux and, in many instances, values recorded here have already been superceded and new processes and data discovered. This is inevitable since modern nuclear physics with its manifold applications is



still young, and a compilation of its measurements and processes must be frequently revised.

The present form of the handbook was expanded beyond a simple compilation of data and formulae in order to make it more intelligible to those who are less conversant with the terminology and details of nuclear physics and tracer methodology. In general, descriptions of processes and instruments have been made rather elementary and with the intention of noting only the principal features. On the other hand, formulae, which are important to a qualitative description or to computations have been included, however complex, with brief statements of their significance and limitations. This has resulted in a considerable volume of descriptive material but it is not intended that the handbook is to be, in any sense, the equivalent of a text book or treatise of the field. We have attempted to compile only a ready reference in which most of the fundamental data and descriptions of processes and instruments will be available.

The biological and medical aspects of tracer methodology is presented in the form of a survey of those isotopes which have been used and those which, because of their convenient properties and biological significance, may reasonably be employed in future research. No effort has been made to present an exhaustive and detailed account since several excellent reviews have already been published; particularly with regard to the clinical literature.

It is realized that many errors still remain to be corrected and in several places, inconsistencies in notation still persist. It is hoped that these will be brought to either the authors or this Command so that they may be rectified in any subsequent revisions.



# I. NUCLEI AND RADIOACTIVITY

## 1. PHYSICAL CONSTANTS

All constants listed are taken directly from, or derived from, values reported by Birge, A. T., Phys. Rev. 13, 233 (1941).

Velocity of light  $c = (2.99776 \pm 0.00004) \times 10^{10} \text{ cm sec}^{-1}$

Electronic charge  $e = (1.60203 \pm 0.00034) \times 10^{-20} \text{ abs. e.m.u.}$   
 $= (4.8025 \pm 0.0010) \times 10^{-10} \text{ abs. e.s.u.}$

Electron mass  $m = (9.1066 \pm 0.0032) \times 10^{-28} \text{ gm}$

Specific electronic charge  $e/m = (1.7592 \pm 0.0005) \times 10^7 \text{ abs. e.m.u. gm}^{-1}$   
 $= (5.2736 \pm 0.0015) \times 10^{17} \text{ abs. e.s.u. gm}^{-1}$

Proton mass  $M_p = (1.67248 \pm 0.00031) \times 10^{-24} \text{ gm}$

Hydrogen atom mass  $M_H = (1.67339 \pm 0.00031) \times 10^{-24} \text{ gm}$

Mass of unit atomic weight ( $1/N_0$ )

$$M_0 = (1.66035 \pm 0.00031) \times 10^{-24} \text{ gm}$$

Ratio proton mass to electron mass

$$M_p/m = 1836.5 \pm 0.5$$

Ratio physical to chemical atomic weight scales

$$r = 1.000272 \pm 0.000005$$

Electron atomic weight

1. physical scale  $A_e = (5.4862 \pm 0.0017) \times 10^{-4}$

2. chemical scale  $A_e = (5.4847 \pm 0.0017) \times 10^{-4}$

Electron rest energy  $mc^2 = 0.5107 \text{ mev}$

Mass unit energy equivalent

$$mu = 1.49 \times 10^{-3} \text{ erg}$$

$$= 931.05 \pm 0.15 \text{ mev}$$

Classical electron radius  $R_e = 2.807 \times 10^{-13} \text{ cm}$



Bohr radius	$R = 0.53 \times 10^{-8} \text{ cm}$
Bohr magneton	$\mu = (0.9273 \pm 0.0003) \times 10^{-20} \text{ erg gauss}^{-1}$
Fine structure constant	$\alpha = (7.2976 \pm 0.0008) \times 10^{-3}$
Compton shift at $90^\circ$	$h/mc = (0.024265 \pm 0.000005) \times 10^{-8} \text{ cm}$
Planck constant	$h = (6.624 \pm 0.002) \times 10^{-27} \text{ erg sec}$
Avogadro number	$N_0 = (6.0228 \pm 0.0011) \times 10^{23} \text{ mole}^{-1}$
Loschmidt number	$L = (2.6870 \pm 0.0005) \times 10^{19} \text{ atmos}^{-1} \text{ cm}^{-3}$
Boltzman constant	$k = (1.38047 \pm 0.00026) \times 10^{-16} \text{ erg deg}^{-1}$
Gas constant	$R_0 = (8.31436 \pm 0.00038) \times 10^7 \text{ erg deg}^{-1} \text{ mole}^{-1}$
Faraday constant:	
1. chemical scale	$F = 96501. \pm 10 \text{ int-coul. gm-equiv.}^{-1}$ $= 96487. \pm 10 \text{ abs.-coul. gm-equiv.}^{-1}$ $= 9648.7 \pm 1. \text{ abs. e.m.u. gm-equiv.}^{-1}$
2. physical scale	$F = 96514. \pm 10 \text{ abs.-coul. gm-equiv.}^{-1}$ $= 9651.4 \pm 1.0 \text{ abs. e.m.u. gm-equiv.}^{-1}$
Gravitational constant	$g = (6.670 \pm 0.005) \times 10^{-8} \text{ dyne cm}^2 \text{ gm}^{-2}$
Standard atmosphere	$A_0 = (1.013246 \pm 0.000004) \times 10^6 \text{ dyne cm}^{-2} \text{ atm.}^{-1}$
Maximum density of water	$d_{\text{max}} = 0.999972 \pm 0.000002 \text{ gm cm}^{-3}$
Density of Hg ( $0^\circ\text{C}$ , standard atmosphere)	$d_0 = 13.59504 \pm 0.00005 \text{ gm cm}^{-3}$



## 2. RADIOACTIVITY UNITS

CURIE: C = 0.66 mm of Rn at 0° C, 760 mm Hg.

Definition: A curie is as the quantity of radon in radioactive equilibrium with 1 gm. of radium.

The evaluation of the curie depends on the determination of the absolute disintegration rate of radium since, by its definition, it is that quantity of radon which disintegrates at the same rate as radium. Measurements of the decay rate at the present time, however, differ in magnitude by as much as 10 per cent. An arbitrary value of  $3.7 \times 10^{10}$  disintegrations per second per gm of radium, therefore, has been recommended by the International Radium Standard Commission until agreement can be reached on the third figure. Initially, the curie applied only to Rn in equilibrium with Ra, however, its extension to the other decay products in equilibrium with Ra was recommended by the Commission in 1930 (1). A curie of any Ra product, therefore, is that quantity of the isotope which decays at the rate of  $3.7 \times 10^{10}$  disintegrations per second.

In addition to the restricted use of the curie recommended by the Commission, it has become widely adopted by common usage as a measure of the quantity of any radioactive isotope. More generally, the fractional unit, millicurie (mc), is used which is the quantity of the isotope that decays at the rate of  $3.7 \times 10^7$  disintegrations per second. The weight or the number of atoms of an isotope equivalent to 1 mc is directly proportional to the half-life:

$$N = 3.7 \times 10^7 \frac{T}{0.693}$$

$$W = 3.7 \times 10^7 \frac{AT}{N_0}$$

$N$  = number of atoms per mc of isotope.

$W$  = weight in gm per mc of isotope.

$T$  = half-life of isotope.

$A$  = atomic number.

$N_0$  = Avogadro's number

The failure to distinguish between total ionizing events and total disintegration has lead to occasional confusion in the use of the curie for isotopes which do not emit alpha particles. When beta particles and gamma rays are emitted, the number of events detected (corrected for geometry, absorption, and efficiency) is usually not equal to the number of disintegrations and it is essential, therefore, to know the decay scheme for the radioisotope. This must include the number of particles per disintegration, the percentage and energy of each, and the per cent internal conversion of gamma rays if they are present. Only when this detailed information is known can the disintegration rate of an isotope be ascertained from measurements of its radiation and its quantity expressed in curies.

Detection of the beta particles, for example, from a radioisotope which emits a beta particle and gamma ray in succession, may lead to disintegration rate which is too high if there are also internal conversion electrons. For the same reason, detection of the gamma rays may well lead to a low value if the conversion co-efficient is unknown. Similarly, the decay rate of a radioisotope which disintegrates by



either positron emission or K capture cannot be determined unless the relative probabilities of the two processes are known, or both the positrons and X-rays are detected.

ROENTGEN:  $r = 83.8 \text{ erg/gm air*}$

$= 1 \text{ esu/cc of dry air*}$

$= 2.083 \times 10^9 \text{ ion pairs/ cc air*}$

$= 1.61 \times 10^{12} \text{ ion pairs/gm air*}$

$= 6.77 \times 10^4 \text{ Mev/cc air*}$

\* dry air at 0° 760 mm Hg

Definition: The Roentgen unit is "that quantity of X- or gamma-radiation such that the associated corpuscular emission per 0.001293 gm of air, dry, 0°, 760 mm Hg produces, in air ions carrying 1 electrostatic unit of quantity of electricity of either sign". (2).

The Roentgen, therefore, is a unit of gamma ray energy loss by ionization in air and is not to be confused with units of radiation intensity or energy, or the energy dissipated in other absorbing media.

ROENTGEN EQUIVALENT PHYSICAL:  $rep = 83.8 \text{ ergs/gm/tissue}$

Definition: The Roentgen equivalent physical is that quantity of corpuscular radiation which produces in tissue per gm of tissue, ionization equivalent to the quantity of ionization for one Roentgen of gamma radiation in air.

The rep is a unit of energy loss by ionization in tissue by radiation other than X- or gamma radiation and therefore applicable to beta

particles, protons, deuterons, alpha particles and neutrons. It is to be noted that, in general, for substances other than dry air at 0°C 760 mm Hg., the rep is not equal to the Roentgen, since energy loss for one Roentgen of gamma radiation in tissue usually is greater than 83.8 ergs/gm (2,3).

RUTHERFORD: 
$$rd = \frac{1}{3.7 \times 10^4} \text{ curie} = \frac{1}{37} \text{ mc}$$

Definition: A rutherford is the quantity of any radioisotope which decays at the rate of  $10^6$  disintegrations per second.

The rutherford has been proposed as a new unit of quantity for all radioisotopes with the exception of the decay products of Ra for which the curie applies (4). Its value is entirely arbitrary but is of the same order of magnitude as quantities used in tracer and therapeutic applications.

ROENTGEN EQUIVALENT MAN: 
$$\text{rem} \approx 0.2 \text{ rem (for fast neutrons)}$$
  

$$\approx 0.1 \text{ n (for fast neutrons)}$$

Definition: The rem is the amount of energy dissipated by fast neutrons in tissue which is biologically equivalent of one r of X- or gamma- radiation in man (or mammals).

The magnitude of the rem is not known with accuracy because of the difficulty in evaluating the biological effects of fast neutrons in man. The approximate value was derived from the mean lethal neutron dose in rats (5), assuming that the radiation resistance is not significantly different in rat and man.

ROENTGEN PER HOUR AT ONE METER: rhm

Definition: The rhm is the quantity of any radioactive substance which emits X -or gamma radiation such that the ionization pro-



duced in air by the radiation at a distance of one meter from the source is equivalent to one r/h.

The rhm is a unit of gamma ray source intensity and should not be confused with units of radiation intensity, absorption, or quality. The gm or cc equivalent of one rhm can be estimated only when the decay scheme is known for the isotope (or isotopes) which emit the gamma radiation. In most cases, therefore, the quantity, in terms of more familiar units, e.g., gm. or cc is not known but the source strength in terms of rhm is unambiguous.

The gm. equivalent of the rhm for Ra with 0.5 mm P filtration is 1.2 gm (5,6,7,8).

n - UNIT:  $n \approx 2.5 \text{ rep}$   
 $\approx 200 \text{ ergs/gm tissue}$

Definition: One n unit is that quantity of fast neutrons which produces, in the Victoreen 100 r thimble chamber, ionization equal to 1 esu/cc of dry air at 0° C, 760 mm Hg.

#### REFERENCES

1. Curie, M., Debierne, A., Eve, A. S., Geiger, H., Kahn, O., Lund, S. C., Meyer, St., Bulherford, E., and Schweidler, E., Rev. Mod. Phys. 69, (1931)
2. Speers, F. W., Brit. J. Radiol. 19, 52 (1946).
3. Lea, D. E., Actions of Radiations on Living Cells, Mac Millan (1947).
4. Condon, E. U., and Curtiss, L. F., Science 103, 712 (1946), Phys. Rev. 69, 672 (1946).

5. Taylor, L. S., and Singer, G., Am. J. Roent. 44, 28 (1940).
6. Gray, L. H., Brit. J. Radiol. 10, 721 (1932).
7. Manyeord, W. V., and Roberts, J. E., Brit. J. Radiol. 10, 365 (1937).
8. White, T. M., Marinelli, L. D., and Failla, G., Am. J. Roent. 44, 889  
(1940).



### 3. PROPERTIES OF NUCLEI

#### A. Stable Isotopes

Examination of the charge, mass, and abundance of existing isotopes has lead to a set of empirical rules governing the structure of stable nuclei so far as an allowed number of protons and neutrons in a stable nucleus are concerned (1.,2). They are understood in a qualitative way from elementary considerations of the binding energies for various combination of neutrons and protons, and are strongly supported by the behaviour of the radioactive isotopes.

The fundamental requirement for stability of nuclei is satisfied when the binding energy is a maximum or, alternatively, the exact mass is a minimum for a given total number of particles. This is equivalent to filling the lowest proton and neutron quantum levels first. If the transformation of a proton to a neutron results in a greater binding energy, (or smaller exact atomic weight), the nucleus is unstable and the transformation will occur through K capture or positron emission. Conversely, beta decay will reduce an excess number of neutrons to protons until the most stable configuration is reached, i.e., until lower lying proton levels are filled. On this basis the isotope rules can be explained and are born out by the modes of decay of the radioactive isotopes.

Formulation of the isotope rules is simplified with the aid of several designations expressing the relation between numbers of neutron and protons. Nuclei with the same number of protons,  $Z$ , but a different atomic weight, or  $A-Z$ , are referred to as isotopes; nuclei with the same number of neutrons ( $A-Z$ ) but different  $Z$  are isotones, and nuclei with the same  $A$  but different  $Z$  are isobars. Nuclei with an even number of both protons and neutrons will be designated by (E,E) and those with even protons and odd neutrons by (E,O).

Similar definitions hold for the designations (0,E) and (0,0).

1. In a first approximation, nuclei contain equal numbers of protons and neutrons, i.e.,  $Z = A/2$ .

For the light elements this rule is followed exactly for the most abundant isotope. This can be understood if it is assumed that the nuclear force binding a neutron and proton (pn) is somewhat greater than the attraction between like particles (pp) and (nn). If the reverse were true, one would expect nuclei to consist wholly of neutrons, or neglecting electrostatic repulsion wholly of protons. Further, if forces between like particles, (pp) and (nn), exist, they must be nearly equal in magnitude. Assuming (nn) were greater than (pp), the maximum binding energy and, hence, greatest stability would occur for nuclei with a greater proportion of neutrons. Actually a variation in  $Z = A/2$  of the order of 10 percent does occur among the isotopes of light elements but this appears to be insufficient to conclude that a significant difference exists between (nn) and (pp).

The most stable configuration with respect to the purely nuclear forces, therefore, are equal numbers of protons and neutrons. In apparent variance with this, however, is the increase in the proportion of neutrons with increasing atomic weight. In the heaviest stable isotopes the ratio of the neutrons reaches a value of 1.6. In these nuclei the repulsive, long range electrostatic fields of the protons becomes a significant factor. The nuclear forces (np), (nn) and (pp) exhibit the property of saturation due to their short range and the finite size of the nucleons. A single particle, therefore, is unaffected by the fields of more distance members of the nucleus and the total binding energy is then proportional to the number of particles, A. The electrostatic field on the other hand, does not show the property of saturation and each proton is affected by the presence of all



other protons, thus contributing to a total electrostatic energy proportional to  $Z^2 / R$  or  $Z^2 / A^{1/3}$  which tends to diminish the effective total binding energy of the nucleus. In the lightest nuclei, the electrostatic energy is less than 0.3 mev per particle whereas the nuclear forces amount to approximately 8.5 mev per particle. For greater atomic weights, the electrostatic energy increases rapidly and the most stable configuration for a given number of particles is one with a greater proportion of neutrons. A balance between the number of protons for a given atomic weight is achieved which provides the maximum total binding energy.

## 2. (E,E) nuclei are the most stable.

This fact is apparent from both their number and their relative abundance. Of the 263 known stable isotopes, this type includes 152, and where several isotopes of an element of even A exist the most abundant are (E,E). This is reasonable on the basis of Pauli's exclusion principle. Two particles can occupy the same state, i.e., with identical spacial coordinates, if their spins are different. Pairs of particles in nearly the same quantum state therefore, can form closed shells in which they are strongly bound. If an odd particle is added, it forms an unclosed shell and is weakly bound by interaction with the closed shells.

## 3. (E,O) and (O,E) nuclei are about equally stable but less so than (E,E).

Stable nuclei of these types are found to occur in about equal numbers; 54 are (E,O) and 52 are (O,E). A single proton or neutron added to an (E,E) nucleus is less strongly bound through interaction with completed shells at lower quantum levels as indicated under rule 2. Nevertheless, such nuclei are stable against K capture or beta emission when the odd particle is added to the next lowest level. The type of stable nucleus which can be formed by the addition of a particle to an (E,E) nucleus of given atomic weight depends upon the next lowest level to be filled. If this is a proton level

but a neutron is added instead, the nucleus is unstable against beta decay and the neutron is transformed to a proton.

4.  $(0,0)$  nuclei, with the exception of  $H_2$ ,  $Li_6$ ,  $B_{10}$ , and  $N_{14}$  are unstable.

The existence of only four such stable isotopes indicates immediately the relative instability of this type of nucleus in all but the lightest elements. If each proton-neutron pair occupy the same quantum state, the resulting nucleus is stable. If, however, the number of neutrons is greater by two or more, they will lie in successively higher levels and will transform by beta emission to the lower lying proton level to form nuclei of the type  $(0,0)$ , therefore, are stable only if the numbers of protons and neutrons are equal. This condition can be found however, only for the lightest elements where the electrostatic forces are still small. In heavier elements equal numbers cannot exist since the electrostatic repulsion then diminishes the nuclear binding energy as compared to equal number of particles but with a greater proportion of neutrons.

5. For any even  $Z$ , there exists only one, or at the most, two stable isotopes of odd  $A$ . If two, they differ by two mass units. Many isotopes of even  $A$  may exist.

6. For any odd  $Z$ , there exists only one, or at most, two isotopes. If two, they differ by two mass units.

7. For any even  $A$ , only two stable isobars may exist and they differ in charge by two units and are even in  $Z$ .

8. For any odd  $A$ , only one stable nucleus exists (no isobars) and its  $Z$  may be even or odd.

A qualitative proof of rules 5,6,7, and 8 follows from energy considerations for the various possible combinations of protons and neutrons. A



nucleus of mass  $A$  is stable only for that combination of protons and neutrons which provides the maximum binding energy or alternatively the minimum exact mass. This can be estimated from the binding energy formula

$$E = a A - b \frac{(A-2Z)^2}{A} - \frac{Z^2}{A^{1/3}}$$

$E$  is a maximum when the last two terms are equal in magnitude and opposite in sign. This requires that  $(A-2Z)/Z \sim A^{2/3}$  or that the excess of neutrons over protons increases as  $A^{2/3}$  for stable nuclei. Further, the binding energy for nuclei of the same  $A$  varies as  $Z^2$  and is therefore a parabola about the most stable value of  $Z$ . For odd  $A$ ,  $Z$  may be even or odd with equal probability as shown by their nearly equal existing numbers. The only isobar which is stable is the one lying nearest the apex of the parabola. All other isobars are unstable and move toward the apex either by  $K$  capture or positron emission until the stable  $Z$  is reached. Alternatively, isobars with neutrons in energy states higher than the next unoccupied proton level, will transform by beta emission until the lowest levels are filled. The converse holds for isobars with excess protons numbers compared to the stable configuration. Such nuclei, capture electrons, transforming protons to neutrons in order to fill lower lying neutron levels.

The binding energy of nuclei with even  $A$  must be represented by two parabolae on the same  $E$  axis; one containing  $(0,0)$  nuclei and a lower curve containing  $(E,E)$  nuclei. From the possible combination of particles,  $(Z,N)$ ,  $(Z-1, N+1)$   $(Z-2, N+2)$  etc., and  $(Z+1, N-1)$ ,  $(Z+2, N-2)$  etc., which can form isobars, those with odd  $Z$  lie on the upper curve and can always transform to a nucleus on the lower curve by beta emission or  $K$  capture. By the same processes, isobars lying far up on the  $Z$ -even curve can cross to a lower

level on the Z-odd curve. By successive transformations of this kind, the isobar is brought finally to one of two possible stable nuclei occupying the lowest levels on the Z-even curve and which differ by two charge units. These nuclei cannot transform into each other despite a possible energy difference, since either beta emission or K capture would take it first to a higher level on the Z-odd curve which is energetically impossible and no process is known for the simultaneous transformation of two charge units without also a change in mass.

An exception to this is found only in the light nuclei  $H_2$ ,  $Li_6$ ,  $B_{10}$ , and  $N_{14}$ . Here, the Z-even and Z-odd curves are nearly superimposed because the electrostatic repulsion is negligible. The lowest state lies at the apex of the Z-odd curve and  $Z = A - Z = N$ .

### B. Mass Defect

Mass spectrographic measurements of the exact weight of nuclei indicate a consistent variation from the integral value given by the atomic weight. The difference between the atomic weight and the exact mass of an isotope,  $M$ , relative to  $O^{16}$  ( $A_0 = 16.00000$ ) is referred to as the mass defect  $\Delta$ ,

$$\Delta = M - A$$

The mass defect is positive only for elements lighter than  $O_{16}$  and for the very heaviest elements. In all other cases it is negative. The variation in the mass defect over the entire mass range is of the order of 0.5 percent or less.



### C. Packing Fraction

The packing fraction,  $f$ , or mass defect per elementary particle is a quantity most frequently employed in experimental practice to express the deviation of the exact isotope mass from the integral atomic weight. It is defined by the relation

$$f = \frac{M - A}{A} = \frac{\Delta}{A}$$

Values of the known packing fractions are given in table and plotted in figure 1. The smooth curve is given by a semi-empirical formula calculated by Fowler (3)

$$f = -79.0 + 4.0 \frac{I}{A} + 242.1 \frac{I^2}{A^2} + \frac{179.8}{A^{1/3}} + 7.42 \frac{Z(Z-1)}{A^{4/3}} \times 10^{-4}$$

$$I = A - 2Z$$

### D. Binding Energy

The exact atomic mass of an atom is in all cases less than the weight of an equivalent number of free neutrons and protons plus  $Z$  electrons. The mass difference is then given by

$$\Delta M = M_{(A,Z)} - 1.008132 Z - 1.00893 (A-Z)$$

where 1.008132 is the mass of a proton plus one electron and 1.00893 is the neutron mass. The apparent decrease in the mass of elementary particles bound in a nucleus is exactly equivalent to the total binding energy of the particles. From Einsteins law of equivalence of mass and energy, the binding energy is then  $E = MC^2$ . One mass unit (mass of  $O_{16}/16$ ) therefore is

$$\begin{aligned} 1 \text{ MU} &= 931.05 \text{ mev} \\ &= 1.49 \times 10^{-3} \text{ erg} \end{aligned}$$

With but few exceptions (D and Li notably) the average binding energy per nucleon in light and medium nuclei is approximately 8.5 mev. In the heaviest nuclei ( $Z > 82$ ), it decreases to approximately 6 mev. Over the greater part of the mass range of nuclei, therefore, the total binding energy is roughly proportional to the number of nucleons or to the nuclear volume.

This is in accord with the assumption of short range nuclear forces between nucleons. Each particle is influenced by the short range attractive fields only of particles next to it and will remain unaffected by more distant particles in the nucleus. To a first approximation, saturation of the nuclear forces then leads to a binding energy which is proportional to the number of particles,  $A$ . Several corrections to  $A$ , the simple proportionality, however, must be made. The unsaturated fields of particles lying at the surface of the nucleus gives rise to a surface tension analagous to that of a liquid drop. The particle is bound to the nucleus by only a portion of its available energy and the remainder cannot contribute to the total binding energy and must be deducted from the first approximation which was made. This correction term is proportional to the surface or to  $A^{2/3}$ . Since the volume to surface ratio increases with the radius or as  $A^{1/3}$ , the relative magnitude of the surface effect in heavy nuclei is smaller than in light nuclei where it affects an appreciable reduction in the binding energy.

The long range electrostatic forces lead to a second term proportional to  $Z^2/A^{1/3}$  due to a uniform volume distribution of the  $Z$  protons. This term is relatively unimportant in light nuclei but increases rapidly with atomic number and becomes, in the heaviest nuclei, a dominant factor in reducing the binding energy and particularly, in the stability against spontaneous



division (see fission). These fields cannot be saturated and each proton, therefore, is influenced by the remaining  $Z-1$  protons in the nucleus.

Finally, a term is included which is based on the observation that the most stable nuclei are those for which  $Z = A/2$ , i.e., the binding energy is a maximum. Nuclei with fewer protons than neutrons will then have a relatively smaller binding energy than for a nucleus containing the same number of particles and  $Z = A/2$ . From the statistical model of the nucleus (1,2,3) this effect is found to be proportional to  $I^2/A$  where  $I = A - 2Z$  is the isotopic number.

On the basis of these factors, several semi-empirical expressions for the total binding energy have been derived. In general form, they follow from Weizacker's method of calculating binding energies (6). Assuming the binding energy is proportional to the number of particles, the isotopic number effect, surface effect, and the electrostatic energy as indicated above, the numerical coefficients for the various terms are then calculated from accurately known values of the exact atomic weight to give the best fit to the experimental data. Three such expressions are given below:

$$E_b = 14.66 A - 20.54 \frac{I^2}{A} - 15.4 A^{2/3} - 0.602 \frac{Z^2}{A^{1/3}} \text{ mev} \quad (2)$$

$$E_b = 15.30 A - 22.55 \frac{I^2}{A} - 16.75 A^{2/3} - 0.69 \frac{Z(Z-1)}{A^{1/3}} \text{ mev} \quad (3)$$

$$E_b = 14.66 A - 77.3 \frac{(Z - A/2)^2}{A} - 13.0 A^{2/3} - 0.58 \frac{Z^2}{A^{1/3}} - \delta \text{ mev} \quad (4)$$

$$\delta = \begin{cases} 0, & A \text{ odd} \\ - \\ + \end{cases} 33.5 A^{-3/4}, A \text{ even} \begin{cases} Z \text{ even} \\ Z \text{ odd} \end{cases}$$

The  $\delta$  term is an empirical correction based on the observed effect of even and odd numbers of protons and neutrons on nuclear stability. The most stable nuclei are those for which  $Z$  and  $A-Z$  are even. Nuclei containing an odd number of protons or neutrons are less stable and those which contain odd numbers of both particles are the least stable. This appears to follow from the periodicity in the structure of nuclei and in particular, how successive shells are filled.

The total binding energy is an important criterion of nuclear stability. At least the lightest nuclei are stable against spontaneous radioactive decay only when their binding energy is greater, i.e., their mass is less, than that for any combination of lighter nuclei containing the same total number of protons and neutrons.

An important application of binding energy is found in the calculation of the exact atomic mass of radioactive nuclei. In the case of beta decay, the energy released is exactly equivalent to the difference in the atomic masses of the initial and product atoms, i.e.,  $E = c^2 (M_Z - M_{Z+1})$ . When a positron is emitted, however, the product atom is lighter by the equivalent energy carried off by the particle together with its rest energy plus the rest energy of an orbital electron which is also lost.  $E = c^2 (M_Z - M_{Z-1} - 2m)$ , where  $m$  is the mass of the positron. Similarly, when an alpha particle is emitted, the energy release is  $E = c^2 (M_{(A,Z)} - M_{(A-4,Z-2)} - 2m)$ .

### E. Nuclear Spin

The resultant angular momentum, or spin, of nuclei is observed in all instances to be either half-integer, or integer multiples of  $h/2\pi$ . More important, the spins of all nuclei with even atomic weight are integer multiples of  $h/2\pi$ , while for nuclei of odd atomic number, the spins are half-integer value. In nearly all cases it is less than  $4h/2\pi$ , and for all



nuclei of the even-even type, it is zero. The resultant spin of a nucleus will be the vector sum of the orbital angular momenta of all the particles and the intrinsic spin of each particle, added according to the vector rules of quantum theory. The orbital angular momentum is always an integer multiple of  $h/2\pi$ , and orientated either parallel or antiparallel to the momenta of other particles in the nucleus. The spins of both the neutron and proton are known from experimental evidence to be  $1/2$  and similarly must be orientated parallel or antiparallel. The contribution of the particle spins to the total nuclear spin will therefore be an integer or half-integer for even or odd numbers of particles.

A sufficiently detailed and consistent model of the nucleus has not yet been formulated which will provide the exact magnitude of the spin for a nucleus containing a prescribed number of protons and neutrons. But the qualitative conclusions outlined above regarding the origin and the necessary magnitudes of nuclear spin are born out by experiment. Further, if the spin of a stable isotope ( $Z, A$ ) is known, it is safe to conclude that the spin of a stable nucleus with which it is isotopic will differ by  $1/2$  the number of excess neutrons, i.e.,  $i = \frac{i_0}{2} (A - A_0)$ , where  $i_0$  is the known spin for the isotope of atomic weight  $A_0$ , and  $A$ , the atomic weight of an unexcited isotopic nucleus.

The spin of a radioactive nucleus, on the other hand, will depend on its state of excitation and will differ from the ground state, usually by integral units of spin. If a beta particle, for example, is emitted, the spin is always reduced by integral units since the ejected beta particle and neutrino each have an intrinsic spin of  $1/2$ . In any nuclear reaction, spin, and angular momentum must be conserved as well as mass and energy. Known values of nuclear spins in units of  $h/2\pi$  are given in table 2 for stable nuclei.

### F. Magnetic Dipole Moment

Assuming the particles within a nucleus to be in motion, it is to be expected that a magnetic field will be produced by the current distribution of at least the charged particles. A single proton moving in a circular orbit with a frequency  $\nu_0$  and angular momentum  $lh/2\pi$  represents a circulating current of magnitude equal to  $i = e \nu_0$  which produces a field equivalent to a magnetic shell with a magnetic moment of

$$\mu = \frac{1 e h}{4 \pi M c} = 1 \mu_0$$

Without a more detailed knowledge of the structure and the motions of particles in nucleus, the magnetic moment must be determined experimentally. Both the protons and neutrons themselves have a magnetic moments which also must be determined experimentally because the charge distribution in elementary particles is not known.

The unit  $\mu_0$  is referred to as the nuclear magneton. Because of the relative magnitudes of the electron and proton masses it is smaller than the Bohr magneton by the factor 1840.

Most experimental methods give instead of  $\mu$ , directly a quantity  $g$ , the nuclear  $g$ -factor, which is related to  $\mu$  by  $\mu = ig$ , where  $i$  is the nuclear spin.

Known experimental values of  $\mu$ , or  $g$  if  $i$  is unknown, are given in table 2.

### G. Electric Quadrupole Moment

From the theory of electrostatics it is known that the potential field of an arbitrary charge distribution can be expressed in a series of terms



of the form

$$V = \frac{eZ}{r} + \frac{ed}{r^2} P_1(\cos \theta) + \frac{q}{r^3} P_2(\cos \theta) + \dots$$

where  $P_1(\cos \theta)$  are Legendre polynomials. At large distances compared to the dimensions of the charge distribution, only the first term, representing a spherically symmetric field, is important since all other terms diminish as  $1/r^2$  or faster. Thus, at distances large compared to a nuclear radius, the electrostatic field is equivalent to a point source of charge  $eZ$ . The second term, or electric dipole moment does exist for nuclei since it vanishes for radially symmetric charge distributions containing charge of only sign.

The third term representing the electric quadrupole may, however, exist for nuclei in which protons are not distributed throughout the nucleus with strict spherical symmetry. A small contribution to the electric is then made by the quadrupole moment which in effect alters the spherically symmetric form of the stronger coulomb field but only within a distance of a few times the nuclear radius. It is reasonable to assume the asymmetry takes the simplest form of distortion of a sphere which is an ellipsoid of rotation, then from electrostatics the nucleus will be "cigar" shaped or a prolate spheroid when  $q$  is positive, and "platter" shaped or an oblate spheroid when  $q$  is negative.

The effect of the quadrupole moment is felt most strongly by orbital electrons in the innermost shells which lie close to the nucleus. This effect was first observed by Schuler and Schmidt (7) in the hyper-fine structure of the Eu isotopes 151 and 153. Differences were found which could not be accounted for by the known perturbations leading to deviations in the interval rule which gave hyper-fine structure terms propor-

tional to  $r^2 \cos^2 (i,j)$ , where  $i,j$ . is the angle between the nuclear spin and the electron angular momentum. This lead Schuler and Schmidt to propose the existence of a quadrupole moment which gave the observed hyperfine structure proportional only to  $\cos^2 (i,j)$  and not  $\mu^2$ .



### References

1. Bethe, H. A., and Bacher, R. F., Rev. Mod Phys. 8, 82 (1936)
2. Mattauch, J., and Fluegge, S., Nuclear Physics Tables, (1946)
3. Fowler, W. A. Private communication. Co-efficients determined from data of Mattauch and Duckworth and Dempster by the method of least squares to give best fit to packing fraction curve.
4. Deutsch, M., notes from Seminar in Nuclear Science and Engineering, M.I.T. (1946)
5. Heisenberg, Rapport du VII Congres Salvay, Paris (1934)
6. Weizsacker, Physik Zeits. 96, 431 (1935)
7. Schuler and Schmidt, Zeits, f. Physik. 94, 457 (1935)

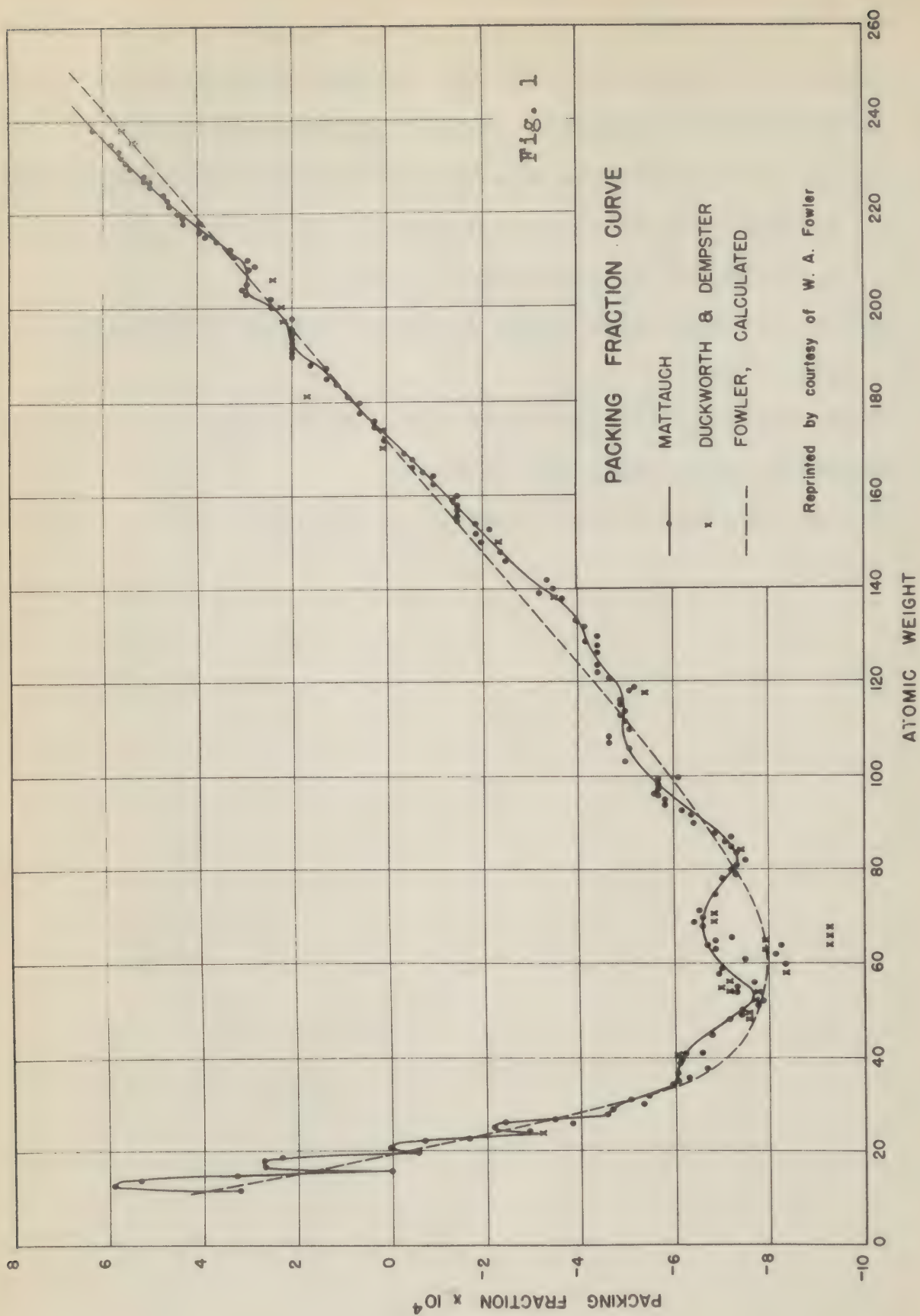


Fig. 1

# PACKING FRACTION CURVE

- MATTAUCH
- × DUCKWORTH & DEMPSTER
- - - FOWLER, CALCULATED

Reprinted by courtesy of W. A. Fowler



# PERIODIC CHART OF THE ELEMENTS

SHORT PERIOD ARRANGEMENT

	O	I	II	III	IV	V	VI	VII	VIII																		
1		H 1.0080								1																	
2	2 He 4.003	3 Li 6.940	4 Be 9.02	5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.0000	9 F 19.00		2																	
3	10 Ne 20.183	11 Na 22.997	12 Mg 24.32	13 Al 26.97	14 Si 28.06	15 P 30.98	16 S 32.06	17 Cl 35.457		3																	
4	18 A 39.944	19 K 39.096	20 Ca 40.08	21 Sc 45.10	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	4															
		Cu 63.57	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916																			
5	36 Kr 83.7	37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc 99	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	5															
		Ag 107.880	47 Cd 112.41	49 In 114.76	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.92																			
6	54 Xe 131.3	55 Cs 132.91	56 Ba 137.36	57 La 138.92	58 Ce 140.12	59 Pr 140.92	60 Nd 144.27	61 Pm 144.91	62 Sm 150.43	63 Eu 152.0	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97	6								
		Au 197.2	79 Hg 200.61	80 Tl 204.39	81 Pb 207.2	82 Bi 208.98	83 Po 209	84 At 210	85 Rn 222	86 Fr 223	87 Ra 226.05	88 Ac 227.05	89 Th 232.04	90 Pa 231.04	91 U 238.03	92 Np 237.05	93 Pu 244.06	94 Am 243.06	95 Cm 247.07	96 Bk 247.07	97 Cf 251.08	98 Es 252.08	99 Fm 257.10	100 Md 258.10	101 No 259.10	102 Lr 262.10	7

Fig. 2

## 5669

LONG PERIOD ARRANGEMENT

# PERIODIC CHART OF THE ELEMENTS

LONG PERIOD ARRANGEMENT

I A		II A		III A		IV A		V A		VI A		VII A		VIII		IX		X		XI		XII			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		
H		He		Li		Be		B		C		N		O		F		Ne		Na		Mg		Al	
1.008	6.940	22.997	24.32	39.096	39.944	50.94	50.94	52.01	52.01	54.94	55.85	58.94	58.94	63.57	65.38	69.72	72.60	74.91	78.96	83.7	85.48	87.63	89.92		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24		

312.



Table 1. STABLE ISOTOPES

element Z	mass number	abundance	atomic mass 016 = 16.000000 error = $10^{-5}$		packing fraction $\times 10^4$	chemical atomic wt
1 H	1	99.98	1.008123	0.6	81.2	1.00785
	2	0.02	2.014708	1.1	73.6	
2 He	3	$10^{-6}$	3.01700	4.	56.7	4.003
	4	100.	4.00390	3.	9.8	
3 Li	6	7.9	6.01697	5.	20.3	6.940
	7	92.1	7.01822	6.	26.0	
4 Be	9	100.	9.01503	6.	16.4	9.02
5 B	10	18.83	10.01677	8.	16.7	10.82
	11	81.17	11.01244	19.	11.3	
6 C	12	98.9	12.00382	4.	3.2	12.010
	13	1.1	13.00751	10.	5.8	
7 N	14	99.62	14.00751	4.	5.4	14.008
	15	0.38	15.00489	21.	3.3	
8 O	16	99.76	16.000000		0.0	16.00000
	17	0.04	17.00450	6.	2.7	
	18	0.20	18.0049	40.	2.7	
9 F	19	100.	19.00452	17.	2.4	19.00
10 Ne	20	90.00	19.99877	10.	-0.6	20.183
	21	0.27	20.99963	22.	-0.2	
	22	9.73	21.99844	36.	-0.7	
11 Na	23	100.	22.99618	31.	-1.7	22.997

element Z	mass number	abundance	atomic mass 016 = 16.000000 error = $10^{-5}$		packing fraction $\times 10^4$	chemical atomic wt.
12 Mg	24	77.4	23.9924	60.	-3.2	24.32
	25	11.5	24.9938	90.	-2.5	
	26	11.1	25.9898	50.	-3.9	
13 Al	27	100.	26.9899	80.	-3.7	26.97
14 Si	28	92.4	27.9866	60.	-4.6	28.086
	29	4.63	28.9866	60.	-4.5	
	30	3.05	29.9832	90.	-5.7	
15 P	31	100.	30.9842	50.	-5.2	30.98
16 S	32	95.0	31.98089	7.	-6.0	32.06
	33	0.74	32.9800	60.	-5.2	
	34	4.2	33.97710	35.	-6.5	
	36	0.016	35.978	100.	-6.1	
17 Cl	35	75.4	34.97867	21.	-6.1	35.457
	37	24.6	36.97750	14.	-6.1	
18 A	36	0.31	35.9780	100.	-6.8	39.944
	38	0.06	37.974	250.	-6.8	
	40	99.63	39.97504	26.		
19 K	39	93.44	38.9747		-6.5	39.096
	40*	0.012	39.9760	100.	-6.0	
	41	6.55	40.974		-6.3	
20 Ca	40	96.96	39.9753	150.	-6.2	40.08
	42	0.64	41.9711		-6.8	
	43	0.15	42.9723		-6.3	
	44	2.07				
	46	0.003				



Element Z	Mass Number A	Abundance	Atomic Mass $0^{16} = 16$		Packing Fraction $\times 10^4$	Chemical Atomic Wt. $0^{16} = 16$
20 Ca	48	0.185	.....		.....	
21 Sc	45	100	44.9689	100.	-6.8	45.10
22 Ti	46	7.95	45.9661	100	-7.4	47.90
	47	7.75	46.9647	100.	-7.5	
	48	73.45	47.9651	50.	-7.3	
	49	5.51	48.9646	60.	-7.2	
	50	5.34	49.9646	40.	-7.6	
23 V	51	100	50.9577	50.	-8.3	50.95
24 Cr	50	4.49	.....		.....	52.01
	52	83.78	51.959		-7.9	
	53	9.43	52.957		-8.0	
	54	2.30	.....		.....	
25 Mn	55	100	54.965		-6.4	54.93
26 Fe	54	6.0	53.960		-7.4	55.84
	56	91.6	55.9568		-7.7	
	57	2.1	56.961		-6.9	
	58	0.28	.....		.....	
27 Co	59	100	.....		.....	58.94
28 Ni	58	68.0	.....		.....	58.69
	60	27.2	59.959		-6.8	
	61	0.1	.....		.....	
	62	3.8	.....		.....	
29 Cu	64	0.9	.....		.....	
	63	69.48	62.956		mean	63.542 $\pm$ .006
	65	30.52	64.955		-8.13	

Element Z	Mass Number A	Abundance	Atomic Mass $O^{16} = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $O^{16} = 16$
30 Zn	64	50.9	63.956	-6.9	65.38
	66	27.3	65.952	-7.4	
	67	3.9	.....	....	
	68	17.4	67.956	-6.5	
	70	0.5	69.954	-6.5	
31 Ga	69	61.5	68.955	-6.5	69.72
	71	38.5	70.953	-6.6	
32 Ge	70	21.2	.....	....	72.60
	72	27.3	.....	....	
	73	7.9	.....	....	
	74	37.1	.....	....	
	76	6.5	.....	....	
33 As	75	100	.....	....	74.91
34 Se	74	0.9	.....	....	78.96
	76	9.5	.....	....	
	77	8.3	.....	....	
	78	24.0	.....	....	
	80	48.0	.....	....	
	82	9.3	.....	....	
35 Br	79	50.53	.....	....	79.916
	81	49.47	.....	....	
36 Kr	78	0.35	77.945	-7.0	83.7
	80	2.01	.....	....	
	82	11.52	81.939	-7.5	
	83	11.52	.....	....	
	84	57.13	83.938	-7.3	
	86	17.47	85.939	-7.1	



Element Z	Mass Number A	Abundance	Atomic Mass $0^{16} = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $0^{16} = 16$
37 Rb	85	72.8	.....	....	85.48
	87*	27.2	.....	....	
38 Sr	84	0.56	.....	....	87.63
	86	9.86	.....	....	
	87	7.02	.....	....	
	88	82.56	.....	....	
39 Y	89	100	.....	....	88.92
40 Zr	90	48.0	.....	....	91.22
	91	11.5	.....	....	
	92	22	.....	....	
	94	17	.....	....	
	96	1.5	.....	....	
41 Nb	93	100	.....	....	92.91
42 Mo	92	15.86	.....	....	95.95
	94	9.12	.....	....	
	95	15.70	94.945	-5.8	
	96	16.50	95.946	-5.6	
	97	9.45	96.945	-5.8	
	98	23.75	97.944	-5.7	
	100	9.62	.....	....	
43 Tc	99				
44 Ru	96	5.68	95.946	-5.7	101.7
	98	2.22	.....	....	
	99	12.81	98.944	-5.7	
	100	12.70	.....	....	

Element Z	Mass Number A	Abundance	Atomic Mass $^{16}_0 = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $^{16}_0 = 16$
44 Ru	101	16.98	.....	....	
	102	31.34	.....	....	
	104	18.27	.....	....	
45 Rh	103	100	.....	....	102.91
46 Pd	102	.8	.....	....	106.7
	104	9.3	103.946	-5.2	
	105	22.6	104.945	-5.2	
	106	27.2	105.945	-5.2	
	108	26.8	107.943	-5.2	
	110	13.5	109.942	-5.2	
47 Ag	107	52.5	106.948	-4.8	107.880
	109	47.5	108.947	-4.8	
48 Cd	106	1.4	.....	....	112.41
	108	1.0	.....	....	
	110	12.8	.....	....	
	111	13.0	.....	....	
	112	24.2	.....	....	
	113	12.3	.....	....	
	114	28.0	.....	....	
	116	7.3	.....	....	
49 In	113	4.5	.....	....	114.76
	115	95.5	.....	....	
50 Sn	112	1.1	.....	....	118.70
	114	0.8	.....	....	
	115	0.4	.....	....	
	116	15.5	115.942	-5.0	



Element Z	Mass Number A	Abundance	Atomic Mass $O^{16} = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $O^{16} = 16$
50 Sn	117	9.1	.....	....	
	118	22.5	117.939	-5.1	
	119	9.8	118.938	-5.2	
	120	28.5	119.94	-6	
	122	5.5	121.944	-4.6	
	124	6.8	123.943	-4.6	
51 Sb	121	56	.....	....	121.76
	123	44	.....	....	
52 Te	120	0.09	.....	....	127.64 ± 0.0
	122	2.43	.....	....	
	123	0.85	.....	....	
	124	4.59	.....	....	
	125	6.87	.....	....	
	126	18.71	.....	....	
	128	31.85	.....	....	
	130	34.51	.....	....	
53 I	127	100	.....	....	126.92
54 Xe	124	0.094	.....	....	131.3
	126	0.088	.....	....	
	128	1.91	.....	....	
	129	26.23	128.946	-4.2	
	130	4.06	.....	....	
	131	21.18	.....	....	
	132	26.98	131.946	-4.4	
	134	10.55	.....	....	
	136	8.95	.....	....	

Element Z	Mass Number A	Abundance	Atomic Mass $O^{16} = 16$	Packing Fraction $\times 10^4$	Chemical Atomic Wt. $O^{16} = 16$
55 Cs	133	100	.....	....	132.91
56 Ba	130	0.101	.....	....	137.36
	132	0.097	.....	....	
	134	2.42	.....	....	
	135	6.6	.....	....	
	136	7.8	.....	....	
	137	11.3	.....	....	
	138	71.7	.....	....	
57 La	139	100	138.955	-3.2	138.92
58 Ce	136	1	.....	....	140.13
	138	1	.....	....	
	140	89	.....	....	
	142	11	.....	....	
59 Pr	141	100	.....	....	140.92
60 Nd	142	25.95	.....	....	144.27
	143	13.0	.....	....	
	144	22.6	.....	....	
	145	9.2	.....	....	
	146	16.5	145.960	-2.8	
	148	6.8	147.961	-2.7	
	150	5.95	149.967	-2.2	
61					
62 Sm	144	3	.....	....	150.43
	147	17	.....	....	
	148*	14	.....	....	
	149	15	.....	....	

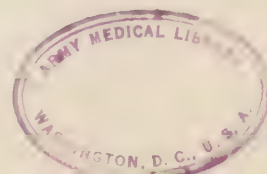


Element Z	Mass Number A	Abundance	Atomic Mass $O^{16} = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $O^{16} = 16$
62 Sm	150	5	.....	....	
	152	26	.....	....	
	154	20	.....	....	
63 Eu	151	49.1	.....	....	152.0
	153	50.9	.....	....	
64 Gd	152	0.2	.....	....	156.9
	154	1.5	.....	....	
	155	21	154.977	-1.5	
	156	22	155.976	-1.5	
	157	17	156.976	-1.5	
	158	22	.....	....	
	160	16	.....	....	
65 Tb	159	100	.....	....	159.2
66 Dy	158	0.1	.....	....	162.46
	160	1.5	.....	....	
	161	22	.....	....	
	162	24	.....	....	
	163	24	.....	....	
	164	28	.....	....	
67 Ho	165	100	.....	....	164.935
68 Er	162	0.25	.....	....	167.2
	164	2.0	.....	....	
	166	(35)	.....	....	
	167	(24)	.....	....	
	168	(29)	.....	....	
	170	(10)	.....	....	

Element Z	Mass Number A	Abundance	Atomic Mass $O^{16} = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $O^{16} = 16$
69 Tm	169	100	.....	....	169.4
70 Yb	168	0.06	.....	....	173.04
	170	2.	.....	....	
	171	(9)	.....	....	
	172	(23)	.....	....	
	173	(17)	.....	....	
	174	(37)	.....	....	
	176	(12)	.....	....	
71 Lu	175	97.5	.....	....	174.99
	176*	2.5	.....	....	
72 Hf	174	0.18	.....	....	178.6
	176	5.30	.....	....	
	177	18.47	.....	....	
	178	27.10	.....	....	
	179	13.84	.....	....	
	180	35.11	.....	....	
73 Ta	181	100	.....	....	180.88
74 W	180	0.135	.....	....	183.88
	182	26.41	.....	....	
	183	14.40	.....	....	
	184	30.64	.....	....	
	186	28.41	.....	....	
75 Re	185	38.2	.....	....	186.31
	187	61.8	.....	....	
76 Os	184	0.018	.....	....	190.2



Element Z	Mass Number A	Abundance	Atomic Mass $O^{16} = 16$	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. $O^{16} = 16$
76 Os	186	1.59	.....	....	
	187	1.64	.....	....	
	188	13.3	.....	....	
	189	16.2	.....	....	
	190	26.4	190.038	+2.0	
	192	40.9	192.038	2.0	
77 Ir	191	38.5	191.040	2.1	193.1
	193	61.5	193.941	2.1	
78 Pt	192	0.8	.....	....	195.23
	194	30.2	194.040	2.0	
	195	35.3	195.040	2.0	
	196	26.6	196.039	2.0	
	198	7.2	198.044	2.2	
79 Au	197	100	197.039	2.0	197.2
80 Hg	196	0.15	.....	....	200.61
	198	10.12	.....	....	
	199	17.04	.....	....	
	200	23.25	200.028	1.4	
	201	13.18	.....	....	
	202	29.54	.....	....	
	204	6.72	.....	....	
	203	29.1	203.057	2.8	204.39
81 Tl	205	70.9	205.057	2.8	
	204	1.5	204.058	2.8	207.21
82 Pb	206	23.6	.....	....	
	207	22.6	.....	....	



Element Z	Mass Number A	Abundance	Atomic Mass 016 = 16	Packing Fraction $\times 10^{14}$	Chemical Atomic Wt. 016 = 16
82 Pb	208	52.3	208.057	2.7	
83 Bi	209	100	209.055	2.6	209.00
84 Po	...	.....	.....	....	.....
85 At	...	.....	.....	....	.....
86 Rn	222*	.....	.....	....	222...
87 Fa	...	.....	.....	....	.....
88 Ra	223*	.....	.....	....	226.05
	224*	.....	.....	....	.....
	226*	.....	.....	....	.....
89 Ac	227*	.....	.....	....	.....
90 Th	232*	100	232.12	5.2	232.12
91 Pa	231*	.....	.....	....	.....
92 U	234*	0.006	.....	....	238.07
	235*	0.720	.....	....	.....
	238*	99.274	238.14	5.6	.....
93 Np	238*	.....	.....	....	.....
94 Pu	239*	.....	.....	....	.....
95 Am	241*	.....	.....	....	.....
96 Cm	242*	.....	.....	....	.....



Table 2. SPIN, MAGNETIC MOMENT, AND QUADRUPOLE MOMENT OF STABLE ISOTOPES

Z	El.	A	spin i units of n	magnetic moment u units of $ne/2mc$	quad. mom. $10^{-24}$ cm <sup>2</sup> .
0	N	1	1/2	-1.9103 $\pm$ 0.0012 (F3, P2, H7, A1, A3)	
1	H	1	1/2 (H8, K1)	2.7896 (K2, M15)	
				$u^n/u^p = -0.6847 \pm 0.0004$	
		2	1 (M15)	0.85647 $\pm$ 0.0003 (A3, K3)	2.73 (K2)
				$u^d/u^p = 0.30702 \pm 0.0001$	
2	He	3			
		4	0 (B5)		
3	Li	6	1 (M2)	0.8213 (R2, R3, M8)	
		7	3/2 (H2, G5, S6, F2)	3.2532 (R2, R3, M8, J4)	
4	Be	9	3/2	-1.176 (K13)	
5	B	10	1	0.597 $\pm$ 0.003 (M9)	
		11	3/2	2.686 $\pm$ 0.005 (M9)	
6	C	12	0 (B17)		
		13	1/2	0.701 $\pm$ 0.004 (H3)	
7	N	14	1 (O1)	0.402 $\pm$ 0.002 (M18, K14)	
		15	1/2 (K12, W3)	-0.280 $\pm$ 0.003 (Z1)	
8	O	16	0 (B17)		
		17			
		18			
9	F	19	1/2 (G1, C1)	2.622 $\pm$ 0.014 (R2, R3, M8)	
10	Ne	20			
		21			
		22			

Z	El.	A	spin i units of n	magnetic moment u units of $\mu_N/2mc$		quad. mom. $10^{-24} \text{ cm}^2$
11	Na	23	3/2 (J1,G3, E1,R1)	2.216 $\pm 0.011$	(K14)	
12	Mg	24				
		25				
		26				
13	Al	27	5/2 (H6,M10)	3.628 $\pm 0.010$	(M10)	
14	Si	28				
		29				
		30				
15	P	31	1/2 (J6,A2)			
16	S	32	0 (B5)			
		33				
		34				
		36				
17	Cl	35	5/2	1.365 $\pm 0.005$	(K15)	$84 \pm 4$ (T7)
		37	5/2	-1.135 $\pm 0.005$	(K15)	$64 \pm 4$ (T7)
18	A	36				
		38				
		40				
19	K	39	3/2 (M6,F2)	0.391 $\pm 0.002$	(K14)	
		40*	4 ( )	-1.290	( )	
		41	3/2 (M1)	0.217 $\pm 0.001$	(M1,K14)	
20	Ca	40				
		42				
		43				



Z	El.	A	spin i units of $\hbar$	magnetic moment $\mu$ units of $\mu_B/2m_e$	quad. mom. $10^{-24}$ cm <sup>2</sup>
20	Ca	44			
		46			
		48			
21	Sc	45	7/2 (S14,K7)	4.8	(K10)
22	Ti	46			
		47			
		48			
		49			
		50			
23	V	51	7/2 (K9)		
24	Cr	50			
		52			
		53			
		54			
25	Mn	55	5/2 (W2,F1)	3.0	(F1)
26	Fe	54			
		56			
		57			
		58			
27	Co	59	7/2 (K8,M11, R5)	2 - 3	(M11)
28	Ni	58			
		60			
		61			
		62			
		64			

Z	El.	A	spin i units of n	magnetic moment u units of n <sub>e</sub> /2mc		quad. mom. 10 <sup>-24</sup> cm <sup>2</sup>	
29	Cu	63	3/2 (R8)	2.5	(S21,S26)	-0.1 <u>+0.1</u> (S21)	
		65	3/2 (R8)	-2.6	(S21,S26)	-0.1 <u>+0.1</u> (S21)	
				$u^{65}/u^{63} = 1.04$			
30	Zn	64					
		66					
		67	5/2 (L1)	0.9	(L1)		
		68					
		70					
31	Ga	69	3/2 (J1,C6)	2.11	(S23,R6)	0.20 (R6)	
		71	3/2 (J1,C6)	2.69	(S23,R6)	0.13 (R6)	
				$u^{71}/u^{69} = 1.270$			
32	Ge	70					
		72					
		73					
		74					
		76					
33	As	75	3/2 (T8,C7, C3)	1.5	(C3,S22)	0.3 (S22)	
34	Se	74					
		76					
		77					
		78					
		80	0 (W5)				
		82					



Z	El.	A	spin i units of $\hbar$	magnetic moment $\mu$ units of $\hbar e/2mc$		quad. mom. $10^{-24}$ cm. <sup>2</sup>
35	Br	79	3/2 (T1,T7)	2.61	(T1,S2)	(720 $\pm$ 10)(T7)
		81	3/2 (T1,T7)	2.61	(T1,S2)	(556 $\pm$ 10)(T7)
$u^{79}/u^{81} = 1.0$						
36	Kr	78				
		80				
		82				
		83	9/2 (K11)	-1.0	(K1,S27)	0.15 (K11,S26)
		84				
		86				
37	Rb	85	5/2 (K16,J8, M19)	1.345 $\pm$ 0.005	(K14)	
		87*	3/2 (H10,M20, H9)	2.741 $\pm$ 0.009	(K14)	
38	Sr	84				
		86				
		87	9/2 (H5)	-1.1	(H5)	
		88	0			
39	Y	89	1/2	$>0.1$		
40	Zr	90				
		91				
		92				
		94				
		96				
41	Cb	93	9/2 (B6)	(3.7)	(B6)	

Z	El.	A	spin i units of n	magnetic moment u units of $ne/2mc$	quad. mom. $10^{-24}$ cm <sup>2</sup>
42	Mo	92			
		94			
		95	1/2		
		96			
		97	1/2		
		98			
		100			
43	Tc	99			
44	Ru	96			
		98			
		99			
		100			
		101			
		102			
		104			
45	Rh	103			
46	Pd	102			
		104			
		105			
		106			
		108			
		110			
47	Ag	107	1/2 (J3)	-0.10	(J3)
		109	1/2 (J3)	-0.19	(J3)

$$u^{109}/u^{107} = 1.93$$



Z	El. A	spin i units of $\hbar$	magnetic moment $\mu$ units of $\mu_N/2mc$	quad. mom. $10^{-24}$ cm <sup>2</sup>
48	Cd 106			
	108			
	110			
	111	1/2 (S5,S7, S10)	-0.65	(J6,B5)
	112			
	113	1/2 (S5,S7, S10)	-0.65	(J9,B5)
			$\mu^{113}/\mu^{111} = 1.0$	
	114			
	116			
49	In 113	9/2 (B1,M7)	6.4	(B1,M7)
	115	9/2 (J2,P1, M7)	5.49	(H1, ) 0.82 (B1,S24)
50	Sn 112			
	114			
	115	1/2	-0.9	( )
	116			
	117	1/2 (T2,S11)	-0.89	(T2)
	118			
	119	1/2 (T2,S11)	-0.89	(T2)
	120			
	122			
	124			
51	Sb 121	5/2 (B3,T3, C3)	3.7	(C3,B5)
	123	7/2 (B3,C3)	2.8	(B3,B5)
			$\mu^{121}/\mu^{123} = 1.316$	

Z	El. A	spin i units of n	magnetic moment u units of n <sub>e</sub> /2mc	quad. mom. 10 <sup>-24</sup> cm <sup>2</sup> .
52	Te 120			
	122			
	123			
	124			
	125			
	126			
	128			
	130			
53	I 127	5/2 (T4,M13)	2.8 (S3)	-0.46 <u>+0.15</u> (S3 S4, M14)
54	Xe 124			
	126			
	128			
	129	1/2 (K6,J7)	-0.9 (K6,J7,B5)	
	130			
	131	3/2 (K6,J7)	0.8 (K6,J7,B5)	0 <u>+0.1</u> (K11,S26)
			$u^{129}/u^{131} = -1.11$	
	132			
	134			
	136			
55	Cs 133	7/2 (K4,C8)	2.572 <u>+0.013</u> (K14)	< 0.3 (S6a,K4)
56	Ba 130			
	132			
	134			



Z	El.	A	spin i units of n	magnetic moment u units of $\mu_N/2m_e$	quad. mom. $10^{-24} \text{ cm}^2$
56	Ba	135	3/2 (B4)	0.837 $\pm$ 0.003	(H4)
		136			
		137	3/2 (B4)	(0.936 $\pm$ 0.003)	(H4)
		138			
57	La	139	7/2 (A4)	2.5 - 2.8	(A5, C4, C5)
58	Ce	136			
		138			
		140			
		142			
59	Pr	141	5/2 (W1)		
60	Nd	142			
		143			
		144			
		145			
		146			
		148			
		150			
62	Sm	144			
		147			
		148*			
		149			
		150			
		152			
		154			

Z	El.	A	spin i units of n	magnetic moment u units of $n\mu/2mc$	quad. mom. $10^{-24}$ cm <sup>2</sup>
63	Eu	151	5/2 (S17)	3.4 (S17,S2)	~ 1.2 (S17,C2)
		153	5/2 (S17)	1.5 (S17,S2)	~ 2.5 (S26)
$\mu^{151}/\mu^{153} = 2.24$					
64	Gd	152			
		154			
		155			
		156			
		157			
		158			
		160			
65	Tb	159	3/2 (S13)		
66	Dy	159			
		160			
		161			
		162			
		163			
		164			
67	Ho	165	7/2 (S18)		
68	Er	162			
		164			
		166			
		167			
		168			
		170			



Z	El. A	spin i units of $\hbar$	magnetic moment $\mu$ units of $\mu_N/2mc$	quad. mom. $10^{-24} \text{ cm}^2$
69	Tm 169	1/2 (S15)		
70	Yb 168			
	170			
	171	1/2 (S26)	0.45 (S27)	
	172			
	173	5/2 (S26)	-0.65 (S27)	3.9 $\pm$ 0.4 (S26)
			$\mu^{173}/\mu^{171} = 1.4$	
	174			
	176			
71	Lu 175	7/2 (S19,G2)	2.6 $\pm$ 0.5 (G2)	5.9 (G2)
	176	$\geq$ 7/2 (H11,M21, L2,S28)	3.8 $\pm$ 0.7 (S28)	6 - 8 (S28)
72	Hf 174			
	176			
	177	$\leq$ 3/2 (R4)		
	178			
	179	$\leq$ 3/2 (R4)		
	180			
73	Ta 181	7/2 (M22)	2.1 ( )	$\sim$ 6 (S29)
74	W 180			
	182			
	183			
	184			
	186			

Z	El.	A	spin i units of n	magnetic moment u units of ne/2mc	quad. mom. 10 <sup>-24</sup> cm <sup>2</sup> .
75	Re	185	5/2 (M4,M5, G4,Z2)	3.3 (S25,S26)	2.8 (S25,S26)
		187	5/2 (M4,M5, G4,Z2)	3.3 (S25,S26)	2.6 (S25,S26)
76	Os	184			
		186			
		187			
		188			
		189	1/2		
		190			
		192			
77	Ir	191	1/2 (V2)	$u^{191}/u^{193} = -1.0$ (V2)	
		193	3/2 (V2)		
78	Pt	192			
		194			
		195	1/2 (F4,V1, J5,T5)	0.6 (J5,T5,S1)	
		196			
		198			
79	Au	197	(3/2) (R7,W4)		
80	Hg	196		0.3 (R7,W4,S16,B5)	
		198			
		199	1/2 (S8,S9)	0.547 $\pm$ 0.002 (M12)	
		200			
		201	3/2 (S8,S9)	-0.607 $\pm$ 0.003 (M12)	0.5 (S30)
				$u^{199}/u^{201} = -0.9018$ (S19)	



Z	El. A	spin i units of n.	magnetic moment u units of $\mu_N/2m_e$	quad. mom. $10^{-24} \text{ cm}^2$ .
80	Hg 202			
	204			
81	Tl 203	1/2 (M23,M17 S31)	1.45	(S24)
	205	1/2 (M23,M17, S31)	1.45	(S24)
82	Pb 204			
	206			
	207	1/2 (K5)	0.6	(M3,R9,S16,B5)
	208			
83	Bi 209	0/2 (B2)	3.6	(S16,S26) -0.39 (S20)
84	Po 210*			

# REFERENCES FOR TABLE 2

- A 1 Alvarez, L.W., and Bloch, F., Phys. Rev. 57, 111 (1940).
- 2 Ashley, M., Phys. Rev., 44, 919, (1933).
- 3 Arnold, W.R. and Roberts, A., Phys. Rev. 71, 878, (1947).
- 4 Anderson, O.E., Phys. Rev. 45, 685, (1934).
- 5 Anderson, O.E., Phys. Rev. 46, 473, (1934).
- B 1 Bacher, R.F., and Tomboulion, D.H., Phys. Rev. 50, 1096; 52, 836 (1937).
- 2 Back, E. and Goudsmit, S., Zeit. f. Physik 47, (174, (1928).
- 3 Badami, J.S., Zeit f. Physik 79, 206, 224, (1932).
- 4 Benson, A.N. and Sawyer, R.A., Phys. Rev. 52, 1127, (1937).
- 5 Bethe, H.A. and Bacher, R.F., Rev. Mod. Phys. 8, 82, (1936).
- 6 Ballard, S.S., Phys. Rev. 46, 806, (1934).
- C 1 Campbell, J.S., Zeit f. Physik 84, 393, (1933).
- 2 Casimir, H., Physica 2, 719, (1935).
- 3 Crawford, M.F. and Bateson, S., Canad. J. Res. 10, 693, (1934).
- 4 Crawford, M.F. and Grace, N.S., Phys. Rev. 47, 536, (1935).
- 5 Crawford, M.F., Phys. Rev. 47, 768, (1935).
- 6 Campbell, J.S., Nature, 131, 204, (1933).
- 7 Crawford, M.F., and Crooker, A.M., Nature, 131, 655, (1933).
- 8 Cohen, V.W., Phys. Rev. 46, 713, (1934).
- E 1 Ellett, A. and Heydenburg, N.P., Phys. Rev. 46, 583, (1934).

- F 1 Fisher, R.A., and Peck, E.R., Phys. Rev. 55, 270, (1939).
- 2 Fox, M. and Rabi, I.I., Phys. Rev. 48, 746, (1935).
- 3 Frisch, O.R., Halban, H.V. Jr., and Koch, J., Phys. Rev. 53, 719, (1938), Nature, London 139, 756, 1021, (1937), 140, 360, (1937).
- 4 Fuchs, B. and Kopermann, H., Naturwiss. 23, 372, (1935).
- G 1 Gale, H.G. and Monk, G.S., Atrophys. J. 69, 77, (1929).
- 2 Gollnow, H., Zeit. f. Physik, 103, 443, (1936).
- 3 Granath, L.P., and Van Atta, C.M., Phys. Rev. 44, 935, (1933).
- 4 Gremmer, W. and Ritschl, R., Z. Instr. -Kd., 51, 170, (1931).
- 5 Guttinger, P., Zeit. f. Physik 64, 749, (1930).
- H 1 Hardy, T.C., Phys. Rev. 59, 686, (abs. 20), (1941).
- 2 Harvey, A. and Jenkins, F.A., Phys. Rev. 35, 789, (1930).
- 3 Hay, R.H., Phys. Rev. 58, 180, (1940).
- 4 Hay, R.H., Phys. Rev. 59, 686, (abs. 19), (1941).
- 5 Heyden, M. and Kopfermann, H., Zeit. f. Physik 108, 232, (1938).
- 6 Heyden, M. and Ritschl, R., Zeit. f. Physik 108, 739, (1938).
- 7 Hoffman, J.G., Livingston, M. St. and Bethe, H.A., Phys. Rev. 51, 214, (1937).
- 8 Hori, T., Zeit. f. Physik 44, 834, (1927).
- 9 Hemmendinger, A. and Smythe, W.R., Phys. Rev. 51, 1052, (1937).
- 10 Kahn, O., Strassman, F., and Walling, E., Naturwiss 25, 189, (1932).
- 11 Heyden, M., and Wefelmeier, W., Naturwiss 26, 612, (1938).
- J 1 Jackson, D.A., Zeit. f. Physik 75, 229, (1932).
- 2 Jackson, D. A., Zeit. f. Physik 80, 59, (1933).
- 3 Jackson, D.A. and Kuhn, H., Proc. Roy. Soc. (A) 158, 372, (1937).



- J 4 Jackson, D.A., and Kuhn, H., Proc. Roy. Soc., (A) 173, 278, (1939).
- 5 Jaeckel, B., Zeit. f. Physik 100, 513, (1936).
- 6 Jenkins, F.A. and Ashley, M., Phys. Rev. 39, 552, (1932).
- 7 Jones, E.G., Proc. Roy. Soc. (A) 144, 587, (1934).
- 8 Jackson, D.A., Proc. Roy. Soc. (A) 139, 673, (1933).
- 9 Jones, E.G., Proc. Phys. Soc., 45, 625, (1938).
- 
- K 1 Kapuscinski, W. and Eymers, J.G., Proc. Roy. Soc. (A) 122, 58, (1929).
- 2 Kellogg, J.M.B., Rabi, I.I., Ramsey, N.F. Jr., and Zacharias, J.R.,  
Phys. Rev. 56, 728, (1939).
- 3 Kellogg, J.M.B., Rabi, I.I., Ramsey, N.F. Jr., and Zacharias, J.R.,  
Phys. Rev. 55, 318, (1939), 57, 677, (1940).
- 4 Kopfermann, H., Zeit. f. Physik, 73, 437, (1931).
- 5 Kopfermann, H., Zeit. f. Physik 75, 363, (1932).
- 6 Kopfermann, H. and Rindal, E., Zeit. f. Physik 87, 460, (1934).
- 7 Kopfermann, H. and Rasmussen, E., Zeit. f. Physik, 92, 82, (1934).
- 8 Kopfermann, H. and Rasmussen, E., Naturwiss. 22, 291, (1934), Zeit.  
f. Physik 94, 58, (1935).
- 9 Kopfermann, H. and Rasmussen, E. Zeitf f. Physik 98, 624, (1936).
- 10 Kopfermann, H. and Wittke, H., Zeit. f. Physik 105, 16, (1937).
- 11 Korsching, H., Zeit. f. Physik 109, 349, (1938).
- 12 Kruger, H., Zeit. f. Physik, 111, 467, (1939).
- 13 Kusch, P., Millman, S., Rabi, I.I., Phys. Rev. 55, 666, (1939).
- 14 Kusch, P., Millman, S., and Rabi, I.I., Phys. Rev. 55, 1176, (1939).
- 15 Kusch, P., and Millman, S., Phys. Rev. 56, 527, (1939).
- 16 Kopfermann, H. Z., Zeits. f. Physik 83, 417, (1933).

- L 1 Lyshede, J.M. and Rasmussen, E., Zeit. f. Physik 104, 434, (1937).  
 2 Libby, W.F., Phys. Rev. 56, 21, (1939).
- M 1 Manley, J.H., Phys. Rev. 49, 921, (1936).  
 2 Manley, J.H. and Millman, S., Phys. Rev. 51, 19, (1937).  
 3 McLennan, J.C., Crawford, M.F., and Leppard, L.B., Nature, 128, 301, (1931).  
 4 Meggers, W.F., Phys. Rev. 37, 219, (1931).  
 5 Meggers, W.F., King, A.S. and Bacher, R.F., Phys. Rev. 38, 1258, (1931).  
 6 Millman, S., Phys. Rev. 47, 739, (1935).  
 7 Millman, S., Rabi, I.I., and Zacharias, J.R., Phys. Rev. 53, 384, (1938).  
 8 Millman, S., Phys. Rev. 55, 628, (1939).  
 9 Millman, S., Kusch, P., Rabi, I.I., Phys. Rev. 56, 165, (1939).  
 10 Millman, S. and Kusch, P., Phys. Rev. 56, 303, (1939).  
 11 More, K.R., Phys. Rev. 46, 470, (1934).  
 12 Mrozowski, S., Phys. Rev. 57, 207, (1940).  
 13 Murakawa, K., Zeit. f. Physik 109, 162, (1938).  
 14 Murakawa, K., Zeit. f. Physik 112, 234, (1939), 114, 651, (1939).  
 15 Murphy, G.M. and Johnston, H., Phys. Rev. 46, 95, (1934).  
 16. Millman, S. and Kusch, P., Phys. Rev. 60, 90, (1941).  
 17 McLennan, J.C., and Crawford, N.F., Proc. Roy. Soc. (A) 132, 10, (1930)  
 18 Millman, S., Kisch, D. and Rabi, I.I., Phys. Rev. 54, 968, (1938).  
 19 Millman, S. and Fox, M., Phys. Rev. 50, 22, (1936).  
 20 Mattauch, J., Naturwiss. 25, 189, (1937).  
 21 Mattauch, S., and Lichtblau, H., Zeit. f. Physik 111, 514, (1939).  
 22 McMillan, E. and Grace, N.S., Phys. Rev. 44, 949, (1933).  
 23 McLennan, J.C. and Allin, E.J. Proc. Roy. Soc. (A) 129, 43 (1930).

- O 1 Ornstein, L.S., and van Wijk, W.R., Zeit. f. Physik 49, 315 (1928).
- P 1 Paschen, F. and Campbell, J.S., Naturwiss. 22, 136 (1934).
- 2 Powers, P.N., Carrol, H., Bayer, H., and Dunning, J.R., Phys. Rev. 51, 371, 1112; (1937), 52, 38, (1937).
- R 1 Rabi, I.I. and Cohen, V.W., Phys. Rev. 46, 707 (1934).
- 2 Rabi, I.I., Millman, S., Kusch, P., and Zacharias, J.R., Phys. Rev. 53, 495 (1938).
- 3 Rabi, I.I., Millman, S., Kusch, P., and Zacharias, J.R., Phys. Rev. 55, 526 (1939).
- 4 Rasmussen, E., Naturwiss 23, 69, (1935).
- 5 Rasmussen, E., Zeit. f. Physik., 104, 229, (1936).
- 6 Renzetti, N.A., Phys. Rev. 57, 753, (1940).
- 7 Ritschl, R., Naturwiss. 19, 690, (1931).
- 8 Ritschl, R., Zeit. f. Physik 79, 1, (1932).
- 9 Rose, J.L., Phys. Rev. 47, 122, (1935).
- S 1 Schmidt, Th., Zeit. f. Physik 101, 486, (1936).
- 2 Schmidt, Th., Zeit. f. Physik 108, 408, (1938).
- 3 Schmidt, Th., Zeit. f. Physik 112, 199 (1939).
- 4 Schmidt, Th., Zeit. f. Physik 113, 140, (1939).
- 5 Schmidt, Th., Naturwiss. 28, 565, (1940).
- 6 Schuler, H., Zeit. f. Physik 66, 431, (1930).
- 7 Schuler, H., and Keyston, J.E., Zeit. f. Physik 67, 433, (1931). 71, 413, (1931).
- 8 Schuler, H. and Keyston, J.E., Zeit. f. Physik 72, 423, (1931).
- 9 Schuler, H., and Jones, E.G., Zeit. f. Physik 74, 631, (1932).



- S 10 Schuler, H. and Westmeyer, H., Zeit. f. Physik 82, 685 (1933).  
 11 Schuler, H. and Westmeyer, H., Naturwiss 21, 660 (1933).  
 12 Schuler, H. and Gollnow, H., Naturwiss. 22, 511 (1934).  
 13 Schuler, H. and Gollnow, H., Naturwiss. 22, 730 (1934).  
 14 Schuler, H. and Schmidt, Th., Naturwiss. 22, 758 (1934).  
 15 Schuler, H. and Schmidt, Th., Naturwiss. 22, 838 (1934).  
 16 Schuler, H., Zeit f. Physik 88, 323 (1934).  
 17 Schuler, H. and Schmidt, Th., Zeit f. Physik 94, 457, (1935).  
 18 Schuler, H. and Schmidt, Th., Naturwiss. 23, 69 (1935).  
 19 Schuler, H. and Schmidt, Th., Zeit. f. Physik 95, 265, (1935).  
 20. Schuler, H. and Schmidt, Th., Zeit. f. Physik 99, 717 (1936).  
 21 Schuler, H. and Schmidt, Th., Zeit. f. Physik 100, 113 (1936).  
 22 Schuler, H. and Marketu, M., Zeit. f. Physik 102, 703, (1936).  
 23 Schuler, H. and Korsching, H., Zeit. f. Physik 103, 434, (1936).  
 24 Schuler, H. and Schmidt, Th., Zeit. f. Physik 104, 468, (1937).  
 25 Schuler, H. and Korsching, H., Zeit f. Physik 105, 168, (1937).  
 26 Schuler, H., Roig, J., and Korsching, H., Zeit. f. Physik 111, 165, (1938).  
 27 Schuler, H. and Korsching, H., Zeit. f. Physik 111, 386, (1938).  
 28 Schuler, H. and Gollnow, H., Zeit f. Physik 113, 1, (1939).  
 29 Schmidt, Th., Naturwiss. 28, 565, (1940).  
 30 Schuler, H., and Schmidt, Th., Zeit. f. Physik 98, 239, (1935).  
 31 Schuler, H. and Keyston, J.E., Zeit. f. Physik 70, 1, (1931).
- T 1 Tolansky, S., Proc. Roy. Soc. (A) 136, 585, (1932).  
 2 Tolansky, S., Proc. Roy. Soc. (A) 144, 574, (1934).  
 3 Tolansky, S., Proc. Roy. Soc. (A) 146, 182, (1934).  
 4 Tolansky, S., Proc. Roy. Soc. (A) 149, 262, (1935); 152, 663, (1935)  
 Proc. Phys. Soc. London, 48, 49, (1936); Tolansky, S. and Forester, G.O.  
 Proc. Roy. Soc. (A) 168, 78, (1938).

- T 5 Tolansky, S. and Lee, E., Proc. Roy. Soc. (A) 158, 110, (1937).
- 6 Townes, C. H., and Smythe, W.R., Phys. Rev. 56, 1210, (1939).
- 7 Townes, C. H., Holden, A.N., Bardeen, J., and Merritt, F.R., Phys. Rev. 71, 644, (1947).
- 8 Tolansky, S., Proc. Roy. Soc. (A) 137, 541, (1932).
- V 1 Valley, G.E., Phys. Rev. 57, 945, (abs. 22).., (1940).
- 2 Valley, G.E. and Anderson, H.H., Phys. Rev. 59, 113, (abs.41).., (1941).
- W 1 White, H.E., Phys. Rev. 34, 1397, (1929).
- 2 White, H.E., and Ritschl, R., Phys. Rev. 35, 1146, (1930).
- 3 Wood, R. W., and Dieke, G.H., J. Chem. Phys. 6, 908, (1938); 8, 351, (1940).
- 4 Wulff, J., Phys. Rev. 44, 512, (1933).
- 5 Wurm, K., Naturwiss. 20, 85, (1932).
- Z 1 Zacharias, J.R. and Kellogg, J.M.B., Phys. Rev. 57, 570, (1940) (abs.74).
- 2 Zeeman, P., Gisolf, J.G., and deBruin, T.L., Nature, 128, 637, (1931).

## 4. GAMMA RAYS

### A. Properties

Gamma rays are an electro-magnetic radiation produced only in nuclear processes; either in the formation of a new nucleus or from decay of excited radioactive nuclei. This distinguishes gamma radiation from X-radiation only in the sense of their origin.

The energy of a gamma photon is directly proportional to the frequency  $E = h\nu$ ,  $= hc/\lambda$  where the factor of the proportionality,  $h$ , is Planck's constant,  $c$ , the velocity of light and  $\lambda$  is the wave length. Also associated with the photon is momentum given by  $p = h\nu/c = h/\lambda$ . In any process involving the interaction of a gamma photon with an atom or an elementary particle, both the energy and momentum must be distributed according to the law of conservation among the various particles and radiations involved. In the collision of a photon with an atom, a larger proportion of the momentum is transferred to the atom and the greater part of energy is transferred to the orbital electrons which are raised to higher energy states or ejected from the atom.

The energy loss of gamma rays in traversing the absorber arises almost entirely from interaction with free, and atomic electrons. Three distinct processes are known which account for the energy loss or energy transfer to electrons:

1. Photoelectric effect. The absorption coefficient,  $\tau$ , is proportional to  $Z^5/E^{7/2}$ . This is the dominant effect in heavy elements for low energy gammas.
2. Compton effect or scattering. Absorption coefficient,  $\sigma$ , is proportional to  $Z/E$ . This is the dominant process in light elements for gammas of medium energies ( $.5 \text{ mev} < E < 3 \text{ mc}^2$ ).



3. Pair production. Absorption coefficient,  $k$ , is proportional to  $Z^2 \log E$ . This is the predominant process in all substances at very high energies, i.e.,  $E > 1.02 mc^2$ . Threshold energy at 1.02 mev ( $2 mc^2$ ).

Three nuclear processes are known to occur which are important to an understanding of the structure of the nucleus but they do not contribute significantly to the gross process of absorption of gamma rays in matter.

1. Photo-disintegration.
2. Excitation of the nucleus.
3. Photo-fission.

The effective total absorption coefficient for gamma rays is the sum of the coefficients,  $\tau$ ,  $\sigma$ , and  $k$ . Since the rate of energy loss from a gamma ray beam is directly proportional to the gamma ray intensity (or number of photons), the intensity decreases exponentially with the distance it traverses through the absorber.

$$I = I_0 e^{-\mu x}$$

$$I_0 = \text{to the initial intensity}$$

$$\mu = \tau + \sigma + k.$$

$$x = \text{linear distance.}$$

The total absorption coefficient varies rapidly with both energy and the atomic number of the absorber.

The range of gamma rays is usually expressed in units of half-value thickness of the particular absorber. One half-value thickness is the quantity of the absorber, either in linear depth or gms per  $\text{cm}^2$ , required to reduce the beam intensity to one-half its initial value.

## B. Photoelectric Effect

The photoelectric effect consists in the interaction of a gamma photon with a bound electron in an atom. The entire energy of the photon is transferred to the electron, ejecting it from the atom with a kinetic energy,  $E_e$ , equal to the difference between the gamma energy,  $h\nu$ , and the electron binding energy  $I$  (ionization potential), i.e.,  $E_e = h\nu - I$ . The orbital electron most likely to participate in this effect is the one whose binding energy is nearest in magnitude to the energy of the incident gamma ray. At energies greater than the highest binding energy (K shell electrons), the contributions from the various levels (K, L, M, etc ) drop off as  $1/\omega^3$ , where  $\omega$  is the rotational frequency.

Exact expressions for calculating the photoelectric cross section,  $\tau$ , are not available but several simple formulae have been given in the form

$$\tau \sim Z^n \lambda^n$$

For a number of elements, the atomic cross sections are given by

$$\tau_a = 1.48 \times 10^{-26} Z^{4.1} \lambda^n$$

$$n = 3.05 \quad \text{for C, N, O}$$

$$n = 2.85 \quad \text{for Na — Fe}$$

$$Z = \text{atomic weight}$$

$$\lambda = \text{wave length in Angstroms}$$

The mass absorption coefficient for the photoelectric effect is given by

$$\left(\mu_p\right)_m = \frac{\tau}{\rho} = 0.0089 \left( \frac{Z^{4.1}}{A} \right) \lambda^n$$

$$= 2.33 \lambda^{3.13} \quad \text{for air} \quad (2)$$

$$= 2.54 \lambda^{3.22} \quad \text{for water} \quad (3)$$

The linear absorption coefficient is given by  $(\mu_p)_1 = \tau_2 N$ , where  $N$  is the number of atoms per cc.

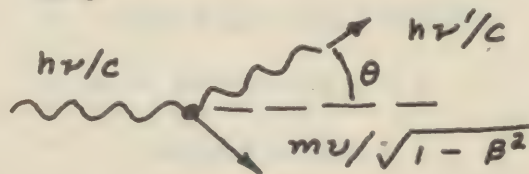
When the absorption coefficient has been measured for one substance, for example lead, it can be calculated for another absorber from the expression:

$$(\mu_p)_1 = 4.07 (\mu_p)_{\text{lead}} \frac{\rho Z^4}{A} \times 10^{-7}$$

### C. Scattering of Gamma Rays

Scattering of gamma rays occurs only with free electrons, or loosely bound electrons. It results in a reduction in the energy of the incident gamma photon and a deflection from its initial direction. The directions taken by the scattered electron and photon and the exchange of energy and momentum are directly related by the requirements of the laws of conservation. The effect was first described independently by Compton (1) who arrived at the expression for the change in wavelength for the scattered photon given below:

$$\lambda' - \lambda = \frac{h}{mc} (1 - \cos \theta) = 0.0242 (1 - \cos \theta) \text{ \AA}$$



where  $h/mc$  is the Compton wave length ( $0.0242 \text{ \AA}$ ). In the soft X-ray region the Compton effect, as it is generally referred to, is not so important as at high energies (of the order of 1 mev) since it is seen that a single collision with an electron is sufficient to increase the wavelength to the order of a Compton wavelength.



Assuming only scattering to be important the intensity,  $I$ , of a beam of gamma rays after traversing a depth,  $x$ , of absorber is given by the usual exponential absorption formula

$$I = I_0 e^{-\mu_s x}$$

where  $\mu_s$  is the scattering coefficient. When referred to a single event i.e., a single electron, the cross section for this process is

$$\sigma_s = \frac{\mu_s}{N}$$

$N$  = the number electrons per cc.

= atomic number  $\times$  number of atoms per cc.

A formula for  $\mu_s$  based on the classical theory was given by Thomson in the form

$$\mu_s = \frac{8 \pi e^4 N}{3 m^2 c^4}$$

$$\sigma_s = 6.62 \times 10^{-24} \text{ cm}^2$$

This formula is valid only at very low energies where the frequency change in collisions is negligible. At all higher energies the cross section is not constant as required by Thomson's formula but varies rapidly with energy.

A quantum mechanical treatment of the process, which is valid for all frequencies of the incident gamma ray, has been carried out by Klein and Nishina (2) on the basis of Dirac's relativistic theory of the electron. The total scattering cross section is found to be the sum of two cross sections. The first, denoted by  $\sigma_s$ , accounts for the reduction in the intensity of a gamma beam by the loss of photons which are scattered out of the direction of the beam. The second, denoted  $\sigma_{as}$ , is the scattering absorption cross section arising from the energy loss of a photon in a scattering process.

The scattering coefficient per electron is given in the form:

$$\sigma_s = \frac{2\pi e^4}{m^2 c^4} \left[ \frac{2(1+a)^2}{a^2(1+2a)} - \frac{1+a}{a^3} \log(1+2a) - \frac{1+3a}{(1+2a)^2} \right]$$

$$a = \frac{h\nu}{mc^2}.$$

$e$  = electron charge.

$m$  = electron mass.

for very low and very high energies, reduced expressions can be used. For low energies;  $a < 1$ ,  $\sigma_s$  can be expanded, (3):

$$\sigma_s = \frac{8\pi e^4}{3 m^2 c^4} \left[ 1 - 2a + 5.2 a^2 - 13.3 a^3 + 32 \frac{24}{35} a^4 + \dots \right]$$

For high energies;  $a \gg 1$ ,  $\sigma_s$  reduces to

$$\sigma_s = \frac{2\pi e^4}{m^2 c^4} \left[ \frac{1}{a} + \frac{1}{2a} \log 2a - \frac{1}{a^2} \log 2a \right]$$

The scattering-absorption coefficient per electron  $\sigma_s$ , is given by the equation:

$$\sigma_s = \frac{2\pi e^4}{m^2 c^4} \left[ \frac{2(1+\alpha)^2}{\alpha^2(1+2\alpha)} - \frac{1+2\alpha}{(1+2\alpha)^2} + \frac{(1+\alpha)(1+2\alpha-2\alpha^2)}{\alpha^2(1+2\alpha)^2} \right. \\ \left. - \frac{4\alpha^2}{3(1+2\alpha)^3} - \left( \frac{1+\alpha}{\alpha^3} - \frac{1}{2\alpha} + \frac{1}{2\alpha^3} \right) \log(1+2\alpha) \right]$$

As for  $\sigma_s$ , similar reduced expression can be used for high and low energies.

For low energies;  $\alpha < 1$ :

$$\sigma_s = \frac{8\pi e^4}{3 m^2 c^4} \left[ \alpha - 4.2 \alpha^2 + 14.7 \alpha^3 - 46 \frac{6}{35} \alpha^4 + \dots \right]$$

For high energies;  $\alpha \gg 1$ :

$$\sigma_s = \frac{2\pi e^4}{m^2 c^4} \left[ \frac{1}{2\alpha} \log 2\alpha - \frac{7}{6\alpha} \right]$$

Both  $\sigma_s$  and  $\sigma_a$  can be converted into the more useful form of scattering coefficient per gm of absorber by multiplying by the number of electrons per gm. The total linear absorption coefficient for scattering is related to the cross section per electron by



$$\mu_s = \sigma \frac{\rho N Z}{A}$$

A = atomic weight,

Z = atomic number.

$\rho$  = density.

If  $\mu_s$  is known for lead, the coefficient for any other substance is found from

$$\mu_s = 0.224 (\mu_s)_{Pb} \frac{\rho Z}{A}$$

#### D. Pair Production

Pair production involves the complete absorption of a gamma photon in the production of an electron and a positron. The process can take place only in the coulomb field of a nucleus although the atom itself does not participate directly in the formation of the particles. Its presence is necessary mainly for the conservation of momentum when the gamma photon transfers its entire energy to the recoil particles.

The cross section of a nucleus for pair production increases as  $Z^2$  but its variation with the gamma ray energy is complicated and is calculated by approximations which are valid over different energy ranges (4, 5, 6). A definite threshold energy exists at  $2 mc^2$  (1.02 mev). Above the threshold, the cross section increases rapidly for energies up to several hundred mev. At very high energies, it increases more slowly; approximately as  $\log E_\gamma$ . A very rough approximation of the nuclear cross section in the lower energy range is given by

$$K = BZ^2 (h\nu - 2 mc^2)$$

B = constant.

and at very high energies by

$$K = DZ^2 \log E$$

$$D = \text{constant.}$$

When the cross section is known for one substance, e.g., Pb, it can be calculated for another absorber with equal accuracy from the relation

$$K = K_{\text{Pb}} \frac{207.2}{(82)^2 11.3} \frac{Z^2}{A}$$

P, Z, A = density, atomic number and atomic weight respectively of absorber.

$K_{\text{Pb}}$  = pair production cross section for lead.

The explanation of the process of pair production is to be found in Dirac's relativistic theory of the electron (7). Dirac showed that the wave equation for the electron admits negative energy states for the electron as well as those of positive energy. The lowest positive state in the continuum of positive energies must necessarily be that equivalent to the rest mass of the electron,  $mc^2$ , since no particle can contain less energy than its rest mass equivalent. Similarly, a highest negative energy state may exist at  $-mc^2$  and below this, there exists an infinity of possible quantum states. Since the existence of electrons in positive states hardly needs demonstration it must be assumed on the basis of Pauli's principle that all negative states are filled and hence, that all space is occupied by an infinite density of negative energy electrons. The existence of such a "sea" of electrons normally could not be demonstrated because their charge forms a field free region. However, if an electron is raised to a positive energy, the unoccupied level or "hole" left behind behaves as a positively charged electron.

The existence of such "holes" or positrons was first observed by Anderson (8) in cosmic radiation. An electron can be ejected from a negative state only by the expenditure of energy at least equal to  $2mc^2$ , corresponding to the transition from  $-mc^2$  to  $+mc^2$ . Gamma rays with energies greater than this, therefore, can excite an electron transition to positive energy states where it is observed together with the "hole" or positron, as a pair of particles of identical mass but opposite charge.

When the positron is brought to rest by the normal processes of energy loss through ionization etc., it recombines with an electron, i.e., a positive energy electron fills the unoccupied level, and gamma radiation is emitted (annihilation radiation) and the particles are no longer detectable.



### E. Secondary Particle Production

The total radiation observed at any depth in an absorber consists of the primary gamma rays together with its secondary radiation of electron (photo-, compton-, and pairs). Since the range of secondary electrons in all absorbers is very small compared to the half-thickness value of gamma rays, the number of recoil particles formed per unit time equals the number absorbed per unit time, i.e., equilibrium is maintained between the primary and secondary radiation intensity. The observed secondary intensity, therefore, decreases exponentially at the same rate as the gamma ray intensity although its actual absorption coefficient is very much greater. The relative magnitudes of the two intensities depends on the atomic number and density of the absorber, or more directly, on the separate absorption coefficients  $u$  and  $u_0$  as expressed by the relation

$$\frac{I}{I_0} = \frac{u_0}{u - u_0}$$

$I, I_0$  = intensities of secondary and primary radiations

$u, u_0$  = absorption coefficients of secondary and primary radiations

It is seen from the expression above that if the gamma rays enter a second medium more dense than the first; for example, from air into lead, the intensity of the secondary radiation will make a transition to a higher relative intensity level before coming to equilibrium. The transition region is characterized by a very rapid increase in electron emission and reaches a maximum at a depth in the absorber approximately equal to maximum range of the recoil electrons. From the surface of second absorber, the variation in the total radiation intensity,  $I$ ,

with depth  $x$  is given by the equation:

$$I = I_0 \frac{u_0}{u - u_0} (e^{-u_0 x} - e^{-ux})$$

$I_0$  = total intensity at surface of absorber.

$u_0$  = absorption coefficient of gamma ray.

$u$  = absorption coefficient of secondary radiation.

#### F. Internal Conversion

Photoelectric emission of electrons from an atom by gamma rays from its own nucleus is termed internal conversion (I.C.). The ejected electrons are observed in a beta spectrograph as a line spectrum consisting of electron groups with highly homogeneous energies which can be distinguished from the continuous background of beta particles from the nucleus when these are present. The orbital electrons with the highest probability for participating in the process are the two K electrons since they lie closest to the nucleus where the gamma intensity is greatest. Other shells, however, may also contribute electrons, particularly in the heavy elements, where, for example, in the natural radioactive elements, conversions have been observed from the shells, K, L, M, N, and O. The conversions, K, LI, and MI similarly have been detected in many of the artificial radioisotopes.

The probability for conversion of a particular gamma is expressed by its total conversion coefficient,  $\alpha$ , which is defined as the ratio of the number of conversion electrons to the number of gammas. The total conversion coefficient is actually the sum of similar coefficients for each electron shell, i.e.,  $\alpha = \alpha_K + \alpha_L + \alpha_M + \dots$ . The magnitudes of the coefficients decrease rapidly with increasing principle and azimuthal quantum



number ( $n + 1$ ) of the electron due mainly to greater distance of electrons with high quantum number from the nucleus. Approximately, the relative intensity of electrons from different shells is given by the ratios:

$$a_K : a_L : a_M = 100 : 15 : 5$$

The total coefficient also decreases rapidly with increasing gamma ray energy and is found, in addition, to depend upon whether the radiation is dipole or quadruple. In all cases, the quadruple radiation exhibits a larger conversion coefficient. Theoretical analyses of internal conversion has been carried out using Dirac's relativistic wave equation of the electron, (9, 10, 11), but calculation of the coefficient is extremely complicated. The theoretical values for electric dipole and quadruple radiation are somewhat lower than the experimental values but the discrepancy may be due to an unknown amount of magnetic multiple radiation which gives a considerably higher coefficient than electric multipole radiation.

The number of conversion electron and gammas of a particular energy,  $h\nu$ , which are emitted per disintegration depends on the probability that the particular gamma ray is emitted as well as on its conversion coefficient. In medium and heavy elements particularly, where many excited levels may exist, the nucleus may decay by one of several alternative sets of transitions involving beta particles, alpha particles, or gamma rays of different energies (see figure 107). Each possible isomeric transition gives rise to its characteristic set of conversion electrons and therefore the number of electrons per disintegration associated with a particular gamma transition is given by the product of fraction of the disintegrations in which it occurs  $p$ , and the conversion coefficient, i.e.,  $\alpha P$ , where  $P \leq 1$ . The value of  $p$  can be obtained from the disintegration schemes when the percentages of the particle emission is known.



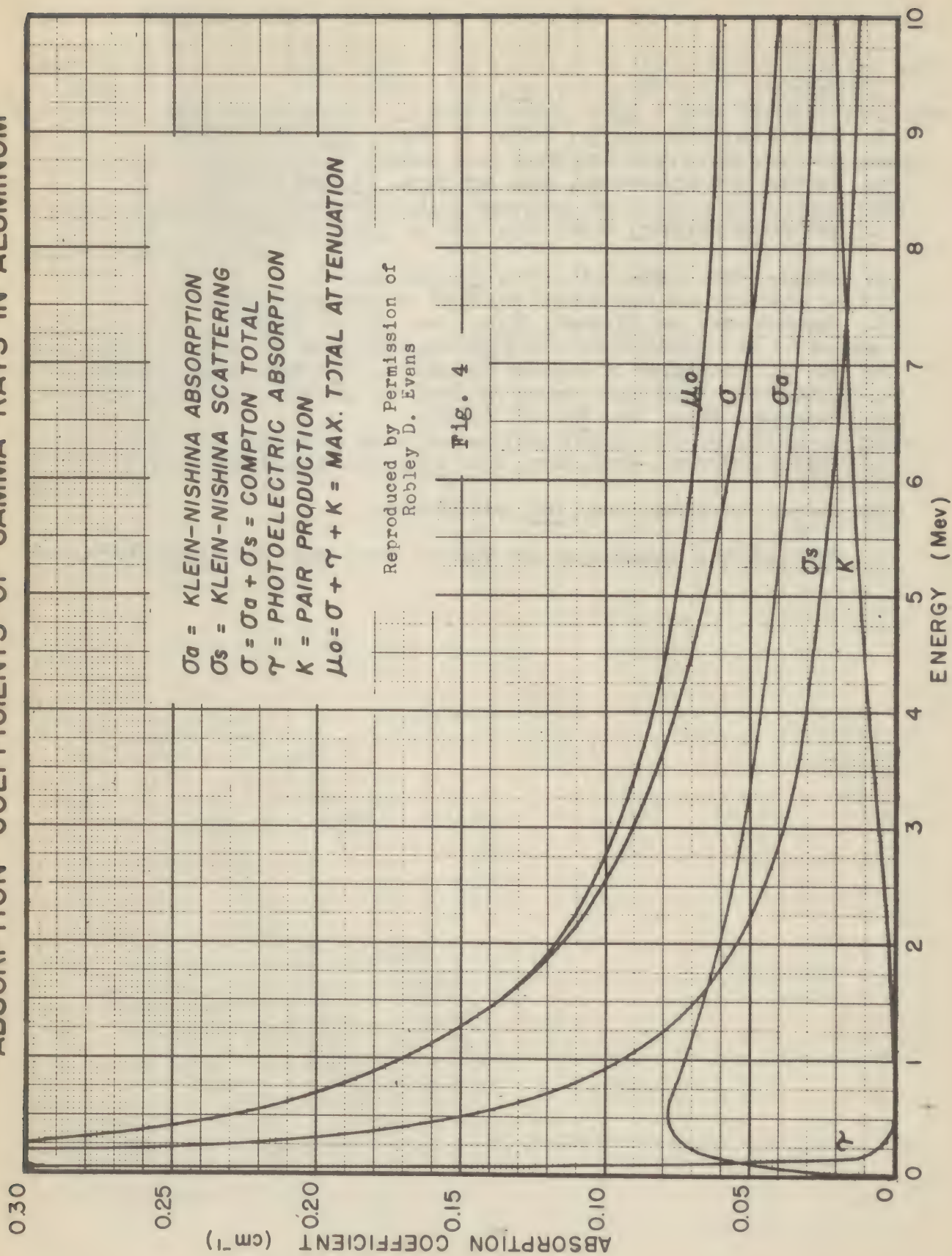
The kinetic energy of the conversion electron is exactly equal to the gamma ray energy,  $h\nu$  minus its binding energy,  $E_b$ :  $E = h\nu - E_b$ . The binding energy to be used is always that of the electron in the residual atom and not the parent. When the intensity is sufficiently high, a beta spectrum will show a set of lines for electrons ejected from different shells by the same gamma. In many instances the electron binding energies can then be determined with considerable accuracy.

It is obviously essential to know the conversion coefficients when the disintegration rate (or absolute quantity) of a radioisotope is to be measured in a sample by counting the beta or gamma radiation. Corrections involving both  $\alpha$  and  $P$  must be made in counting either beta particles or gamma rays.

## REFERENCES

1. Compton, A.H., Phys. Rev. 21, 482 (1923).
2. Klein, O., Nishina, Y., Zeits. f. Physik 52, 853 (1929).
3. Kustner and Trubesteen, Ann. and Phys. 28, 385 (1937).
4. Bethe and Heitler, Proc. Roy. Soc. A. 146, 83 (1934).
5. Bethe, Proc. Camb. Phil. Soc. 30, 112 (1937).
6. Oppenheimer, and Plesset, Phys. Rev. 44, 53 (1933).
7. Dirac, Principles of Quantum Mechanics, Clarendon Press, Oxford, (1935).
8. Anderson, Phys. Rev. 43, 491 (1933).
9. Taylor and Mott, Proc. Roy. Soc. 138, 665; 142, 215 (1933).
10. Hulme, Proc. Roy. Soc. 138, 643 (1932).
11. Hulme, Mott, Oppenheimer and Taylor, Proc. Roy. Soc. 155, 315 (1936).

# ABSORPTION COEFFICIENTS OF GAMMA RAYS IN ALUMINUM

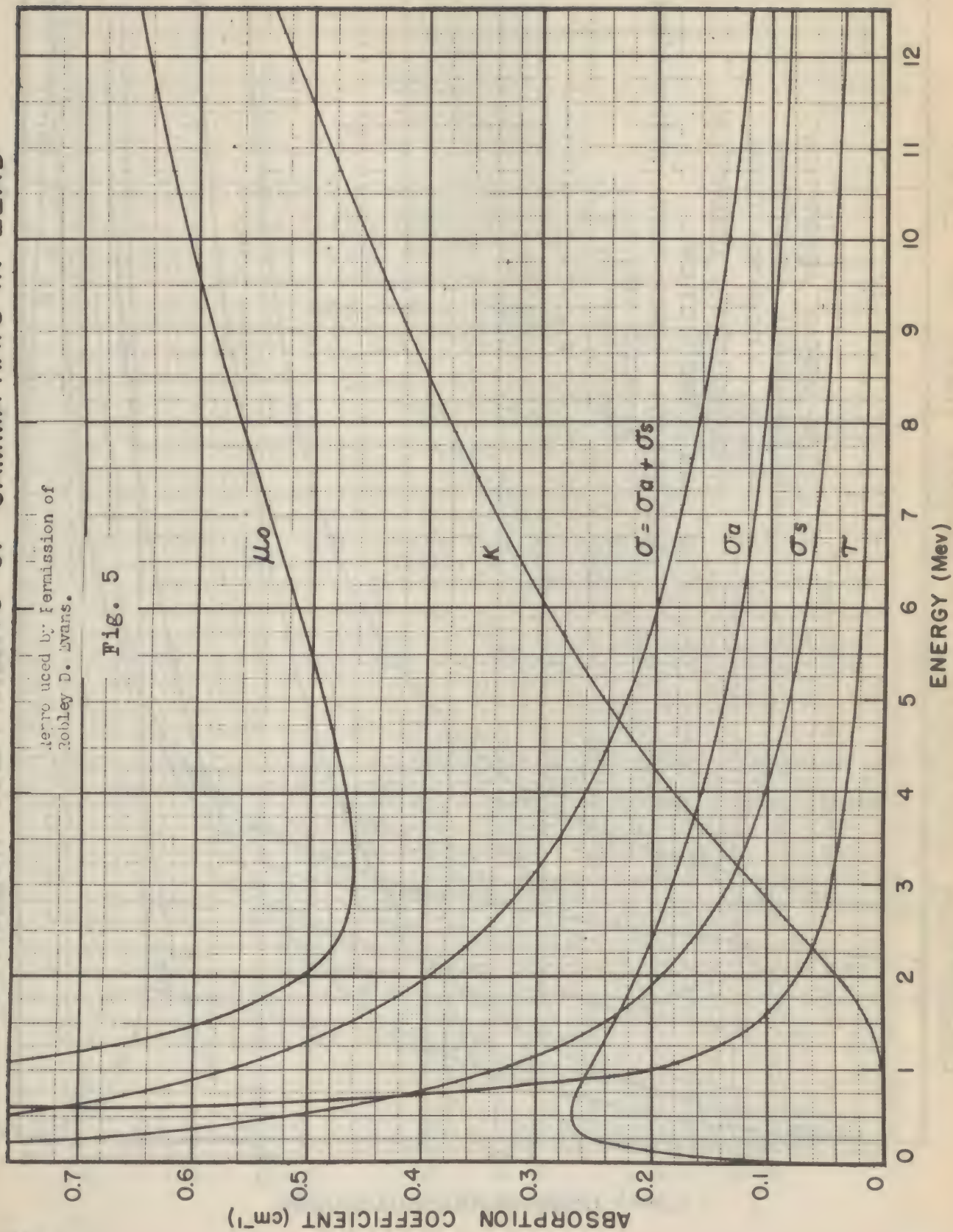




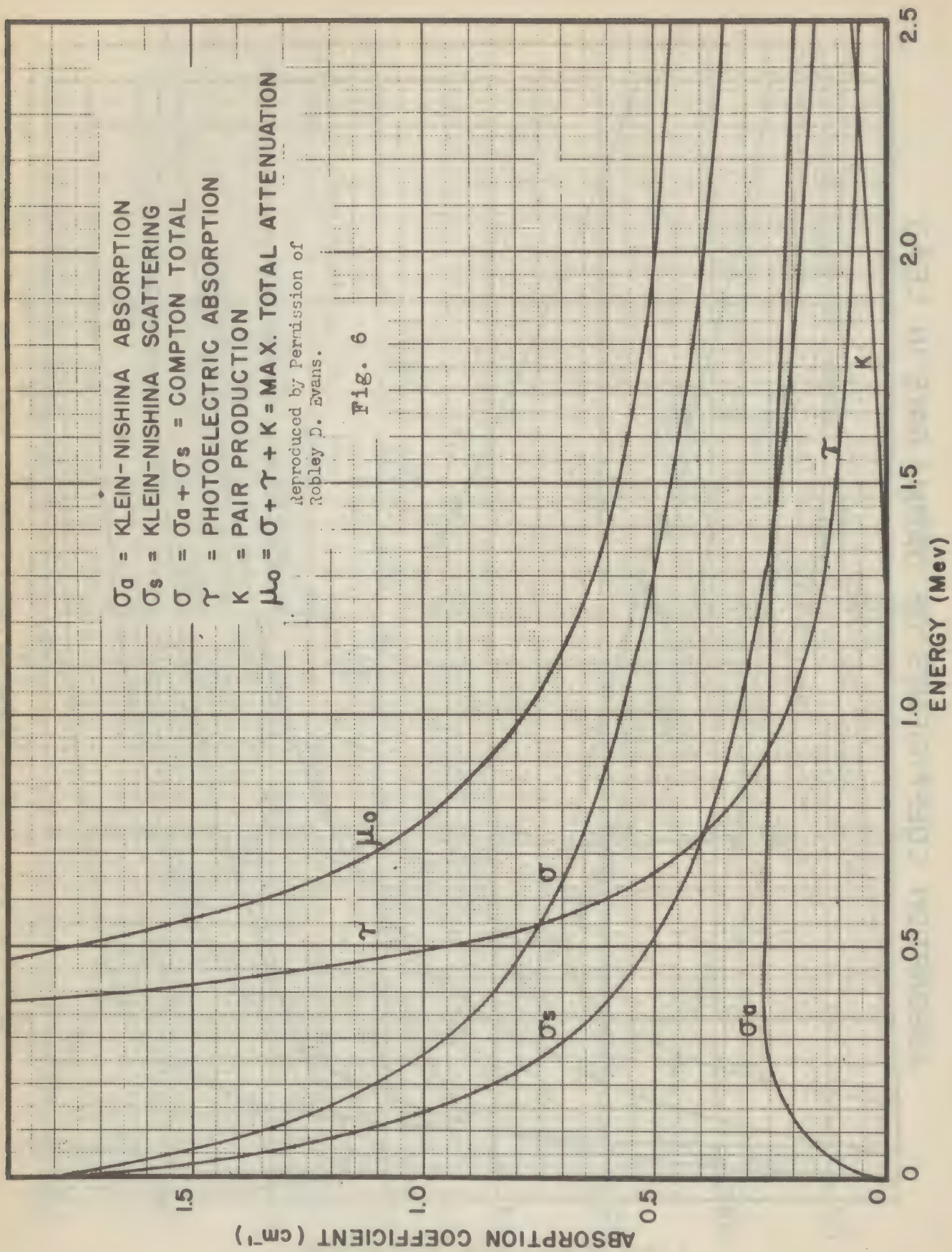
# ABSORPTION COEFFICIENTS OF GAMMA RAYS IN LEAD

Reprinted by permission of  
Robert D. Evans.

Fig. 5

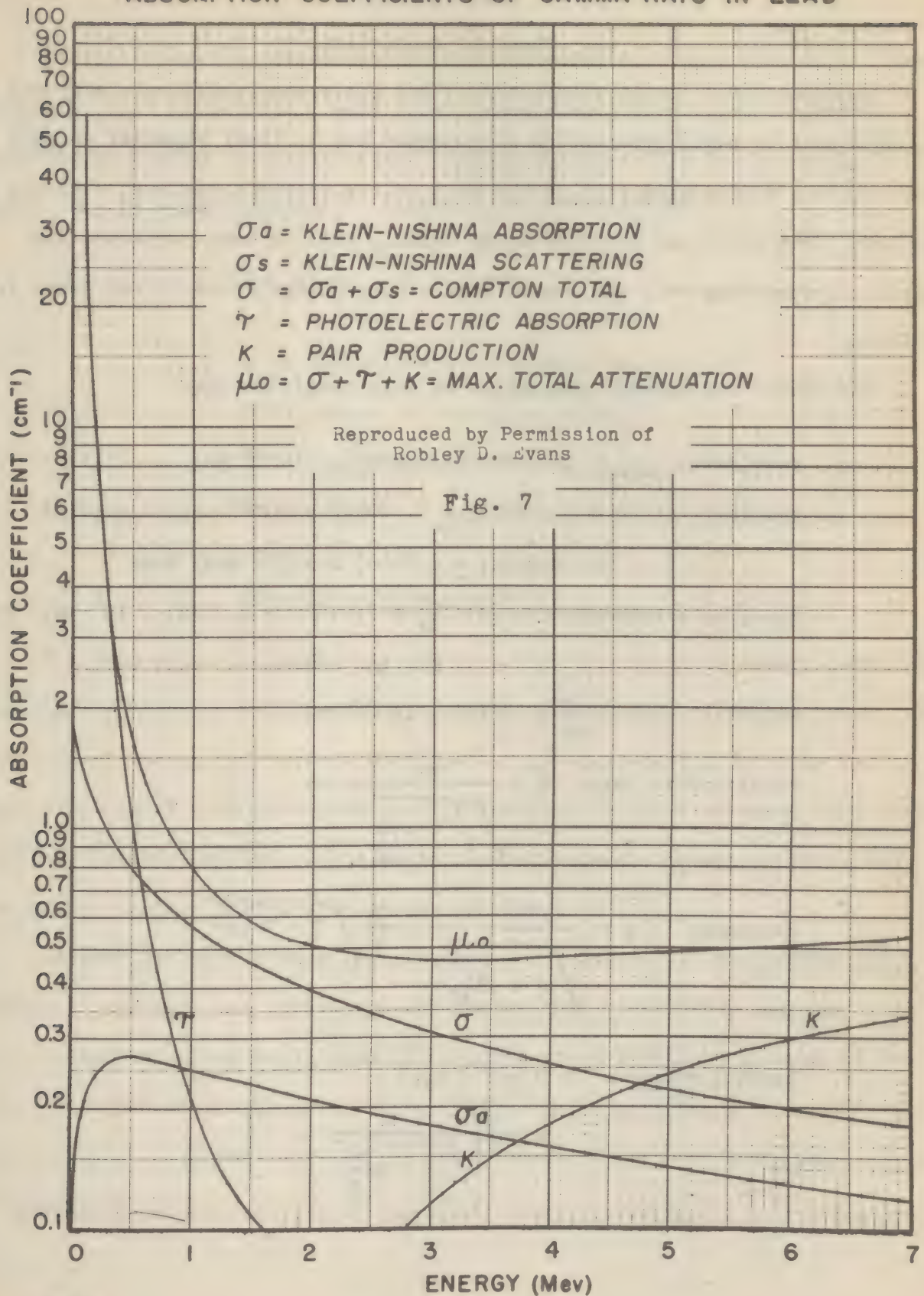


# ABSORPTION COEFFICIENTS OF GAMMA RAYS IN LEAD





# ABSORPTION COEFFICIENTS OF GAMMA RAYS IN LEAD





## 5. BETA PARTICLES

### A. Physical Properties

Beta particles (negative electrons) and positrons (positive electrons) are identical in their interaction with matter and in their physical properties with the single exception of the sign of the charge associated with the particle. The following sections apply equally well to beta particles and positrons, observing only the proper sign of the charge where it may occur in formulae.

The static and dynamic properties of beta particles are:

$$\text{rest mass: } m_0 = (0.910660 \pm 0.0032) \times 10^{-28} \text{ gm} \quad (1)$$

$$\text{charge: } e = (1.602033 \pm 0.60034) \times 10^{-29} \text{ abs. emu.} \quad (1)$$

$$= (4.80251 \pm 0.0010) \times 10^{-10} \text{ abs. esu.}$$

$$\text{specific electronic charge: } \frac{e}{m} = (1.7502 + 0.0005) \times 10^7 \text{ abs. emu.} \\ \text{per gm.} \quad (1)$$

$$\text{radius: } r = \frac{e^2}{m_0 c^2} \approx 2.8 \times 10^{-13} \text{ cm.}$$

$$\text{relativistic mass: } m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\text{momentum: } p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{T}{c} \sqrt{1 + 2 \frac{mc^2}{T}}$$

$$\text{kinetic energy: } T = mc^2 - m_0 c^2 \\ = mc^2 \left[ \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1 \right]$$

$v$  = velocity of beta particle in cm per sec.

$c$  = velocity of light in cm per sec.

Energy is usually expressed in electron volts although units of  $H$  are frequently used since this quantity can be measured directly with the beta spectrometer and in the Wilson cloud chamber operated in a uniform magnetic field. The relation between  $H$  and energy is given by:

$$H\rho = \frac{10^4}{3} \sqrt{E^2 + 1.02E}$$

$H$  = magnetic field strength in Gauss.

$\rho$  = radius of curvature in cm.

$E$  = energy in mev.

This relation is plotted in figure 8 for more convenient conversion.

#### B. Absorption Processes

The absorption of beta particles in matter results from energy losses by three main processes: excitation and ionization of atoms of the absorber, and radiation of energy by the beta particle during acceleration in close collisions with nuclei. At sufficiently high energies ( $\sim 1$  mev or more) some loss occurs by nuclear excitation but it is negligibly small except at energies comparable to those encountered in cosmic rays.

At energies less than a few mev, radiative losses are negligible and the principle processes are excitation and ionization. No clearly defined range-energy relation exists as it does for heavy charged particles because of the great variation in energy loss per collision, which may vary from zero to almost the total beta particle energy, and because of the more pronounced effects of scattering.

### C. Ionization

The probable energy loss per unit length of path by ionization has been calculated by Bethe (2) which, including the relativity correction, has the form:

$$-\frac{dE}{dx} = \frac{2 \pi e^4 N Z}{m v^2} \left[ \log \frac{E^3}{m c^2 (1 - \beta^2)} - \beta^2 \right]$$

$I$  = average ionization potential of absorber.

$Z$  = atomic number.

$N$  = number of atoms per cc.

$E$  = total energy of electron (kinetic plus rest mass).

$m$  = electron mass.

$v$  = electron velocity.

$e$  = electron charge.

$\beta = v/c$ .

For very high energies where  $E \gg mc^2$ , i.e.,  $v \approx c$ , this reduces to

$$-\frac{dE}{dx} = \frac{2 \pi e^4 N Z}{m c^2} \log \frac{E^3}{2 m c^2 I^2}$$

### D. Specific Ionization

The total ionization, produced by a beta particle is the sum of the primary ions produced directly by the particle, subsequent ionization by the primary ions, and those produced by bremsstrahlung or X-rays from the initial electron. In general, the range of secondary ions is a small fraction of a mm in air because of their small recoil energy, so that



the majority of ions lie close to the path of the beta particle. The total ionization, however, is several times the number of primary ions formed. Primary ionization can be observed directly in the Wilson Cloud chamber since a single primary ion together with its secondary ions form a single droplet.

Curves for primary and total ionization are given in figure 8a. For energies greater than 1 mev, there is little change in the specific ionization which remains almost constant at approximately 25 ion pairs per cm path in air at NTP.

### E. Radiative Losses

At energies greater than several million electron volts, radiative collisions account for an appreciable fraction of the energy loss. For these energies, ionization losses increase very slowly, approximately as  $\log E$ , whereas radiative loss increases directly in proportion to  $E$ . At energies higher than 10 - 100 mev depending on the atomic number of the absorber, radiation is the principle process for energy loss. Radiation emitted directly from beta particles traversing an absorber is known as bremsstrahlung and is the source of the continuous X-ray spectrum.

A formula for radiation energy loss has been derived by Bethe and Heitler (3) which appears to be valid for energies up to roughly  $137 mc^2$  ( $\sim 65$  mev).

$$-\frac{dE}{dx} \sim NEZ^2 \log AE$$

$N$  = number atoms per cc.

$E$  = energy of beta particle

$Z$  = atomic number

$A$  = constant

Considerable straggling is observed since an electron may lose nearly all of its energy in a single radiative collision or it may make many collisions with

small energy loss. The energy loss in a particular collision depends upon the velocity of the particle, the distance from the struck nucleus, and the nuclear charge,  $Z$ . The effective value of  $Z$  for heavy nuclei is somewhat smaller than the number of protons because of the screening effect by the orbital electrons on the nuclear charge.

Neglecting the logarithmic terms in the formulae for ionization and radiative loss, a simple and approximate formula is found for the ratio of ionization to radiative losses.

$$\frac{\left(\frac{dE}{dx}\right)_I}{\left(\frac{dE}{dx}\right)_R} = \frac{EZ}{1600 mc^2} = \frac{EZ}{800}$$

$E$  = energy in mev

#### F. Nuclear Excitation

Energy loss by nuclear excitation and capture is negligibly small in terms of absorption of a beta particle beams for all energies which have been observed. Its principle importance is in the determination of nuclear energy levels. Theoretical cross sections for nuclear excitation are of the order of  $10^{-9}$  barns and for capture, of the order of  $10^{-7}$  barns.

#### G. Absorption of Beta Particles of Homogeneous Energy

A well defined range does not exist for beta particles due to the great variation in energy loss per collision and, to a greater degree, due to scattering. Nevertheless, a useful range can be found since the absorption curve for a beam of initially homogeneous beta particles is roughly linear. An extrapolated, or maximum, range is determined by plotting the number of particles (counts) against thickness of absorber and extending the linear portion of the curve to the axis (or background count). Figure 9 gives the observed



extrapolated ranges of beta particles determined from the line spectra of various radioisotopes. An empirical relation for extrapolated range in aluminum, fitting these data within  $\pm 5\%$  over the energy range from 0.5 to 3 mev is (4)

$$R = 0.52E - 0.09$$

$$R = \text{gm Al/cm}^2$$

$$E = \text{energy in mev}$$

The range in aluminum for energies between 0.01 and 0.15 is given approximately by the relation (4)

$$R = 0.15 E - 0.0028$$

#### H. Absorption of Inhomogeneous Beta Particle Beams

The absorption curve for beta particles of inhomogeneous energy decreases more rapidly than the curve observed for homogeneous beams of the same maximum energy. The shape and extrapolated range of such curves is of particular importance in its application to beta particles emitted from radioisotopes for which the energy distribution is continuous from zero to a well defined maximum energy. The observed absorption curve for beta particles from these sources is accurately represented by an exponential over most of the range but has a finite and definite termination. The exponential character of the absorption can only be interpreted as a fortuitous effect due to a combination of the Fermi energy distribution of the emitted particles, scattering, and absorption by radiative and ionization energy loss. To a close approximation the beta intensity  $I$  (e.g. counts per min) at a depth  $x$  in an absorber is given by:

$$I = I_0 e^{-ux}$$

$$I_0 = \text{initial intensity (or counts)}$$

$$u = \text{absorption co-efficient in cm}^{-1}$$

$$x = \text{depth of absorber in cm.}$$



A more convenient form is found in terms of the mass absorption co-efficient,  $\mu/\delta$ , where  $\delta$  is the absorber density in gm per cc. This co-efficient is insensitive to the atomic number,  $Z$ , of the absorber; increasing very slowly with increasing  $Z$ . An empirical relation for the mass absorption co-efficient valid for the light elements with a probable error of 0.2 mev is (4)

$$\frac{\mu}{\delta} = \frac{22}{E_m^{1.33}}$$

$E$  = maximum energy

and in terms of the half-value thickness,  $d$ , i.e. where  $I = 0.5 I_0$ , it is

$$d = 0.693 \frac{d}{\mu} = 0.032 E_m^{1.33}$$

These empirical relations are not valid for very low energies ( $E_m < 0.5$  mev) where scattering is more pronounced nor at very high energies ( $E_{max} > 5$  mev) where energy loss by radiative collision becomes important.

The maximum range of beta particles from radioisotopes with  $E_{max}$  within the range 0.6 - 5 mev can be found from an empirical relation for aluminum determined by Feather (5)

$$R = 0.54 E_m - 0.16$$

$R$  = range in gms Al per  $cm^2$

### I. Scattering of Beta Particles by Nuclei

The elastic scattering of beta particles has presented a difficult problem both in theory and in measurement. Because of the small mass of the electron compared to a nucleus, large deflections in a single collision may occur frequently, particularly for beta particles of low energies scattered by heavy elements. For this reason, the effects of elastic scattering should

never be overlooked in the evaluation of measurements on beta particles.

Single elastic collisions of slow electrons with nuclei can be calculated from Rutherfords' formula (6) since elastic collisions involve only interaction of the Coulomb fields of the electron and nucleus. For collisions of high speed beta particles where relativistic effects are important, a formula has been given by Mott (7) for the intensity (or number) of beta particles scattered into the solid angle,  $d\omega$  at an angle  $\theta$  from the initial direction:

$$n(\theta) = n_0 N \left( \frac{e^2 Z}{2mv^2} \right)^2 (1 - \beta^2) \left[ \frac{1}{\sin^4 \frac{\theta}{2}} - \frac{\beta^2}{\sin^2 \frac{\theta}{2}} + \pi \beta \alpha Z \frac{\cos^2 \frac{\theta}{2}}{\sin^3 \frac{\theta}{2}} \right]$$

which, for small angles and all values of  $Z$ , reduces to

$$n = n_0 N \left( \frac{e^2 Z}{2mv^2} \right)^2 (1 - \beta^2) \csc^4 \frac{\theta}{2}$$

and for large angles and small  $Z$ , is:

$$n = n_0 N \left( \frac{e^2 Z}{2mv^2} \right)^2 (1 - \beta^2) \left( 1 - \beta^2 \sin^2 \frac{\theta}{2} \right) \csc^4 \frac{\theta}{2}$$

$$\alpha = 2\pi e^2 / hc = 1/137$$

$n$  = number of particles per  $\text{cm}^2$  scattered into solid angle  $d\omega$   
at an angle  $\theta$ .

$n_0$  = initial number of particles per  $\text{cm}^2$  in beam.

$N$  = number of atoms per cc.

$Z$  = atomic number of scatterer.

$m$  = electron mass

In all cases the scattering co-efficient is proportional to  $\frac{Z^2}{v^2} (1 - \beta^2)$ .

These formulae apply only to very thin foils in which the probability of more than one collision is small. A criterion for determining if single scattering can be expected in an experimental arrangement has been given by Wentzel (8) which provides that the minimum observed angle of deflection  $\theta$  and the foil thickness,  $t$ , must be chosen so that  $\theta \geq 4\varphi$  where

$$\cot \frac{\varphi}{2} = \frac{m v^2}{e^2 Z} \sqrt{\frac{2}{\pi n t}}$$

$m$  = electron mass.

$e$  = electron charge.

$Z$  = atomic number.

$n$  = number atoms per cc.

$t$  = foil thickness in cm.

This criterion permits several deflections through angles of the order of but determines the magnitudes of  $\theta(\min)$  and  $t$  so that the contributions due to multiple collisions is negligible at an angle  $\theta$  where the scattered beam is detected. For aluminum the maximum thickness for single scattering is approximately  $2 \mu$  ( $0.54 \text{ mg per cm}^2$ )

Single deflections of low energy beta particles through large angles ( $>90$  degrees) may be expected with a finite but very small probability in "thin" foils but in "thick" scatterers where multiple scattering is important, an



appreciable fraction of an incident beam of particles is backscattered, or deflected through more than 90 degrees. The coefficient of reflection,  $R_\theta$ , may be defined by the expression  $(I_0 - I_r)/I_0$  where  $I_0$  = incident beta intensity and  $I_r$  is the backscatter intensity. For most substances the reflection coefficient has a value between 0.1 and 0.5 depending upon the atomic number and density.

This effect is particularly important in measurements of radioactive samples and in the preparation of standards. The observed activity or counting rate is profoundly affected by the backing material. The backscatter from platinum and lead for example, is found to be 20 - 50 per cent greater than from aluminum, depending upon the counter geometry.

#### J. Scattering by Electrons

The resonance scattering of beta particles by stationary electrons (essentially free thermal or bound electrons) must necessarily include the spin (1/2) and obey Fermi statistics. Non-relativistic scattering formulae, i.e. for identical coulomb fields, have been given by Mott (9) for the cases of known or unknown spin orientation of the two particles. If  $P_s$  is the probability that an electron is deflected into a solid angle,  $dw$  at an angle  $\theta$ , using symmetric wave functions, and  $P_a$  is the corresponding probability using anti-symmetrical wave functions:

$$P_s = \left( \frac{2e^2}{mv^2} \right)^2 \cos \theta \left[ \frac{1}{\sin^4 \theta} + \frac{1}{\cos^4 \theta} + \frac{2A}{\sin^2 \theta \cos^2 \theta} \right]$$

$$P_a = \left( \frac{2e^2}{mv^2} \right)^2 \cos \theta \left[ \frac{1}{\sin^4 \theta} + \frac{1}{\cos^4 \theta} - \frac{2A}{\sin^2 \theta \cos^2 \theta} \right]$$

$$A = \cos \left[ \frac{2\pi e^2}{h\nu} \log \tan^2 \theta \right]$$

Case I. If angle between spins of beta particles and the stationary electrons is not known, the number of particles deflected into solid angle,  $dw$ , at an angle  $\theta$  is

$$n(\theta) = n_0 N Z \frac{1}{4} (P_s + P_a)$$

Case II. If angle, , between spin of the beta particle and electron is known, the total probability of deflection into solid angle  $dw$  at angle  $\theta$  is

$$P = \frac{1}{4} (1 - \cos \varphi) P_s + \frac{1}{4} (3 + \cos \varphi) P_a$$

Case III. Spins parallel:

$$P = P_a$$

Case IV. Spins anti-parallel:

$$P = \frac{1}{2} (P_s + P_a)$$

$n$  = initial number particles per  $\text{cm}^2$  per sec.

$N$  = number atoms per cc.

$Z$  = atomic number

$v$  = electron velocity

$m$  = electron mass

$e$  = electron charge

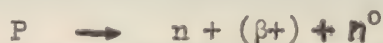
Case IV is identical to the classical scattering formula. Comparing the formulae for scattering by nuclei and electrons, the ratio of the relative intensities (number of particles, or cross sections) is

$$\frac{n(\text{nuclear})}{n(\text{electrons})} \sim Z$$

Hence, for hydrogen, the two processes contribute equally; for heavier elements the scattering is almost wholly by nuclei.

### K. Beta Decay

The emission of beta particles or positrons occurs only during the decay of an excited nucleus and is never associated with the primary process in which the excited nucleus is formed by bombardment. The latter process takes place in less than  $10^{-10}$  seconds whereas the probable time for beta and positron emission is of the order of a second and longer. When a nucleus is formed from bombardment by n,p,d, or alpha particles it may contain an excess of either protons or neutrons as compared to a stable nucleus of the same mass number and consequently its mass is greater and its binding energy less than the corresponding stable species (see Stable Isotope Rules). If the replacement of a proton by a neutron leads to a smaller atomic weight (greater binding energy), the transformation will occur according to the scheme:



Conversely, if the replacement of a neutron with a proton results in a more stable nucleus, the transformation is:



In both cases the excess energy (mass) is carried off by the neutrino,  $n^0$ , and the positron or beta particle. If a beta particle is emitted, the nuclear charge increases by one unit and if a positron; it decreases by one unit. In calculating the exact mass reduction by these processes, the exact atomic weights (neutral atom) can be used in beta emission since the loss of the rest mass of the beta is exactly compensated by the gain of an orbital electron. In positron emission, however, a correction for twice the rest mass must be made since



both the positron and an orbital electron are lost.

The emission of the hypothetical neutrino, first postulated by Pauli, is required for the conservation of energy, spin, and statistics. The emission of a beta particle or positron corresponds to a level transition in the excited nucleus involving a discrete quantity of energy yet the emitted particles are observed to possess any energy from zero up to the transition energy,  $E_{\text{max}}$ . It is necessary to assume therefore, that the neutrino carries off an energy in each instance equal to the difference between the particle energy (rest + kinetic) and the transition energy. Furthermore, beta and positron emission always results in a reduction of the spin,  $i$ , of the residual nucleus by units of  $\hbar/2\pi$ , i.e., 0, -1, -2, ..., while the intrinsic spin of the particle is a half unit. It must be assumed, therefore, that the neutrino spin is one-half. A similar observation holds for the statistics in that the statistics of the residual nucleus remains unaltered while the electron obeys Fermi statistics.

The properties of the neutrino deduced from experiment are then

mass:  $= 0$  or  $\ll$  electron mass

Charge: none

spin:  $1/2(\hbar/2\pi)$

Magnetic moment:  $< 1.5 \times 10^{-4}$  Bohr Magnetron

statistics: Fermi

With the aid of the neutrino hypothesis and the transformations ( $p \rightarrow n$ ), ( $n \rightarrow p$ ), Fermi (10) developed a theory of beta decay analogous to the emission of light. The theory provides a means of calculating the probability of the transformation i.e., the mean life for decay, the energy distribution of the particles and a set of selection rules for determining if a transition

is allowed or forbidden.

Assuming the neutrino mass to be negligible, the probability of emission per unit time of a beta particle with energy between  $E$  and  $E + dE$  is given by Fermi's theory in the form

$$PdE = \frac{g^2}{2\pi^3} \left| Q \right|^2 f(Z,E) E(E^2 - 1)^{1/2} (E_0 - E)^2 dE$$

$E$  = electron energy in units of  $mc^2$ .

$$= (mc^2 + mv^2) / mc^2.$$

$E_0$  = maximum energy in units of  $mc^2$

$g$  = constant.

The factor  $Q$  is a matrix element involving the proper functions,  $U_n$ , of the neutron and  $U_m$ , of the proton to which is transforms integrated over all space and spin coordinates:

$$Q = \int U_n^* U_m e^{-i(P_n + P_e) \cdot \frac{2\pi r}{h}} dV$$

If the proton or neutron which is transformed remains in nearly the same quantum state after beta emission,  $Q$  is nearly unity. If the initial and final quantum states are different,  $Q$  is less than unity and it is zero when a transition between two states is impossible, i.e., the transformation of a proton or neutron in state  $n$  to a neutron or proton in state  $m$  is forbidden. For most light elements in which comparatively few states exist at this level of excitation, it can be regarded generally as unity (or zero if it is energetically impossible) the factor  $f(Z,E)$  is a correction to the electron wave function in the presence of the strong Coulomb field of the nucleus. In light elements, the correction is small and  $f(Z,E)$  is of the order of unity. For  $Z = 0$   $f(0,E) = 1$ . Its general form is given by:

$$f(Z,E) = 2(2PR)^{2(s-1)} (1+s) e^{\frac{\pi\alpha ZE}{P}} \frac{\left[ \Gamma\left(s + \frac{i\alpha ZE}{P}\right) \right]^2}{\left[ \Gamma(2s+1) \right]^2}$$



$P$  = electron momentum in units of  $mc$  i.e.,  $(E^2 - 1)^{1/2}$ .

$R$  = nuclear radius in units of  $h/2mc$ .

$$= 1.5 \times 10^{-13} A^{1/3} \frac{2\pi mc}{h}.$$

$Z$  = atomic number (negative for positrons).

$\alpha$  = fine structure constant.

$$= \frac{2\pi e^2}{hc} = 1/137$$

$$S = (1 - \alpha^2 Z^2)^{1/2}$$

$\Gamma$  = gamma function.

The Fermi theory provides for a continuous distribution in energy for the ejected particles from  $E = mc^2$  ( $mv^2 = 0$ ) to a maximum energy,  $E_0 = mc^2 + mv^2$ , corresponding to the total transition energy for the particular nucleus and transition. The most probable beta energy is found to be  $E_0/2$  and near both zero kinetic and the maximum energy, very few particles are to be expected. A difference in the numbers of positrons and beta particles should be found in the low energy end of the spectrum for medium and heavy element because of the strong effect of the nuclear coulomb field. Fewer low energy positrons will be observed since, once formed, they derive addition energy from the repulsive electrostatic field. Conversely, a greater number of beta particles are observed because faster particles loss energy to the field.

Considerable difficulty was experienced at first in attempting to verify the theoretical distribution. The observed curve appeared to show a maximum at  $E_0/3$  rather than  $E_0/2$  and in some isotopes, the general form of the curve was somewhat altered. Most of the difference between the observed and theoretical energy curves arose from the great technical difficulty in measuring the beta particles in the low energy portion of the spectrum because of the more pronounced effects of scattering and straggling. Unless the greatest



precautions are taken, self-absorption in the source and even the thinnest mica counter windows shifts the maximum of the curve to lower energies. Observations are sometimes further complicated in radioisotopes in which two or more beta particles (or positrons) are emitted per disintegration or when conversion electrons (line spectra) are present (see Gamma Rays). When a nucleus can decay by one of several possible beta transitions, the observed energy distribution is a superposition of the several Fermi curves (11). Conversion electrons, on the other hand, can be readily identified since they form a peak of high intensity and small energy spread superimposed on the continuous distributions.

An approximate expression for energy distribution for  $E_0 < 2 \text{ mev}$  has been given in the form (12)

$$PdE = A E^{1/2} (1 + 2E) (1+E)^{1/2} (E_0 - E)^2 dE.$$

$A = \text{constant for each isotope}$

A form more useful for plotting experimental data is to be found in the reduced equation given by Kurie (13)

$$\left(\frac{N}{F}\right)^{1/2} = A - B (E + 1)$$

$N$  = number of particles observed in each successive momentum interval.

$E$  = energy in units of  $mc^2$ .

$A, B$  = experimental constants.

In terms of the number,  $N^1$ , of particles per unit energy range, it is

$$\frac{N^1}{pEF} = C - DE$$

$P$  = momentum in units of  $mc$  for energy  $E$ .

$C, D$  = experimental constants.

Plotting  $(N/F)^{1/2}$  or  $(N/pEF)^{1/2}$  against  $E$ , a straight line of negative slope is obtained if the particles follow a Fermi distribution in energy. The intercept on the energy ordinate corresponds to  $E_0 = 1/2 mv^2 + mc^2$ .

The theoretical mean life,  $\tau$ , for beta (positron) decay is found by integrating the probability of emission per unit time over the whole range of energy.

$$\frac{1}{\tau} = P_t = \int_0^{E_0} P dE = q^2 |Q|^2 F(Z, E_0)$$

$P_t$  = total probability that a particle of any energy is emitted per unit time.

The exact form of the function  $F(Z, E_0)$  is inconveniently complicated for calculation and approximations valid over certain ranges of  $Z$  and  $E_0$  have been suggested:

1.  $F(Z, E_0) \gg 1 + 2.5 Z^2 \times 10^{-5}$ , (14, 15):

$$F(Z, E_0) \sim u (\bar{p})^{2(S-1)} \left[ v - w (E_0 - 1)^3 \right]$$

$$u = \frac{4\pi(2R)^{2(S-1)} |aZ| (1+S)}{(2S!)^2 |1 - e^{-2\pi aZ}|}$$

$$v = \frac{1}{30} (E_0^5 - 10 E_0^2 + 15 E_0 - 6)$$

$$w = \frac{\pi}{3} |aZ| |e^{2\pi aZ} - 1|^{-1}$$

$\bar{p}$  = average momentum.

2.  $Z$  small,  $(E_0 - 1) \ll 1$ ; (14, 16):

$$F(0, E_0) = 0.216 (E_0 - 1)^{7/2}$$

3.  $Z > 0$ ,  $(E_0 - 1) \ll 2 \pi^2 \alpha^2 Z^2$ , for  $\beta^-$  only (14):

$$F(Z, E_0) = uv (\bar{p})^{2(S-1)} (1 - e^{-2\pi\alpha Z})$$

4.  $Z > 0$ ,  $(E_0 - 1) \ll 2 \pi^2 \alpha^2 Z^2$ , for  $\beta^+$  only (14):

$$F(Z, E_0) = uv (\bar{p})^{2(S-1)} (1 - e^{-2\pi\alpha Z}) e^{-2\pi \frac{|\alpha Z|}{[0.6(E_0 - 1)]^{1/2}}}$$

In all cases the probable life for beta or positron emission decreases rapidly with increasing maximum energy,  $E_0$ .

#### L. Selection Rules for Beta Decay

Nuclear transitions of the form  $n \rightarrow p$ , or  $p \rightarrow n$  involved in beta emission are classed as allowed, first, second, or higher order forbidden depending upon the relative probability of the process. Empirically, a transition is classed by comparison of the half-life with beta-emitters of nearly the same atomic number.

The product of the half-life  $t$ , and the function,  $F$ , defined in the preceding section, is roughly constant for a particular transition class in either light, medium or heavy nuclei. An increase in the order of magnitude however is found for gross increase in the atomic number, due mainly to the more pronounced effect of the coulomb field with increasing  $Z$ . The orders of magnitude of  $F t$  for allowed, first and second forbidden transitions in light, medium, and heavy nuclei are given in the table below (15):



Transit.	Ft		
	light	medium	heavy
Allowed	$3 \times 10^3$	$5 \times 10^4$	$2 \times 10^5$
1st forbid.	$2 \times 10^5$	$2 \times 10^6$	$1 \times 10^7$
2nd forbid.	$5 \times 10^7$	$1 \times 10^8$	$\sim 10^9$

Theoretical selection rules for beta decay are based on the form of the matrix element,  $Q$ , which determines the change in state accompanying beta emission. For many light beta-emitters,  $Q \sim 1$ , since the residual proton remains in nearly the same state as the initially transformed neutron. This is much less likely in heavy nuclei. If the change in state is considerable,  $Q \ll 1$ , and the transition is to some degree (1st, 2nd or higher) forbidden. The principle change in state to affect the probability of transition is the change in total angular momentum,  $J$ , of the nucleus, and the parity change. The rules originally proposed by Fermi are:

allowed	$\Delta J = 0$	no parity change
1st forbidden	$\Delta J = 0, \pm 1, (0 \rightarrow 0 \text{ forbidden})$	parity change
2nd forbidden	$\Delta J = \pm 1, \pm 2, (1 \leftrightarrow 0 \text{ forbidden})$	no parity change

A second set of selection rules proposed by Gamow and Teller (17) based on a different choice of matrix element,  $Q$ , appears to find better support from the experimental data. The simplest results of the G-T rules, without reference to the matrix elements, are:

allowed	$\Delta J = 0, \pm 1, (0 \rightarrow 0 \text{ forbidden})$	no parity change
1st forbidden	$\Delta J = 0$	
	$0, \pm 1 (0 \rightarrow 0 \text{ forbidden})$	parity change
	$0, \pm 1, \pm 2, (0 \rightarrow 0, 1 \leftrightarrow 0)$	
	$1/2 \rightarrow 1/2 \text{ forbidden}$	

2nd forbidden  $\Delta J = \pm 2$

$\pm 2, \pm 3$  ( $0 \leftrightarrow 2$  forbidden)

no parity change

### M. K-Capture

The inverse process to normal beta decay is the absorption by the nucleus of an orbital electron accompanied by the emission of a neutrino (18). Once in the nucleus the electron does not retain its intrinsic form but is essential as in positron emission, to the transformation of a proton to a neutron. The electron absorbed is one of the two K electrons since they spend more time within and near the nucleus than the L, and M electrons; and hence, have a higher probability for capture when the process is energetically possible. K capture leads to a nucleus one charge unit smaller and to an atomic weight which is smaller than the initial atom by only mass equivalent of the increase in binding energy.

The energy of the absorbed K electron has a definite value which is its rest energy minus its atomic binding energy, i.e.,  $E_e = (1 - \alpha^2 Z^2)^{1/2}$  in units of  $mc^2$ . Thus, the neutrino must be ejected with a kinetic energy equal to the sum of the total electron energy and the nuclear transition energy and is therefore monoenergetic. Its value is given by:

$$E_n = E_z - E_{(Z-1)} + E_e - 1 = E_0 + E_e$$

$E_0$  = transition energy in units of  $mc^2$ .

$E_z$  = energy equivalent of exact atomic weight of initial nucleus  
in units of  $mc^2$ .

$E_{(Z-1)}$  = energy equivalent of exact atomic weight of final nucleus  
in units of  $mc^2$ .

Although K capture frequently competes with positron emission in the same transition, in some instances it is the only process energetically possible. Thus, only K capture is possible if the transition involves less energy than equivalent to the rest mass of an electron (0.5 mev) i.e., when

$$1 - E_e < E_Z - E_{(Z-1)} < 2 \quad (\text{units of } mc^2)$$

while both processes are possible if  $E_0 > 1$ .

The theoretical treatment and calculations of K capture mean-life and probabilities are essentially the same as for beta decay. The probability of a transition depends principally, as in beta decay, on the accompanying change in total angular momentum,  $\Delta J$ , of the nucleus; i.e.,  $U = 0$ , allowed,  $\pm 1$ , first forbidden;  $\pm 2$ , second forbidden; etc. The mean life is given by (15,19)

$$\frac{1}{T} = \frac{g^2}{2\pi^3} |Q|^2 f_k$$

$Q$  = matrix element ( $\sim 1$  for light elements).

$g$  = experimental constant.

For allowed transitions,  $\Delta J = 0$ :

$$f_k = 2 \pi (\alpha Z)^{2(S+1)} (E_0 + E_e)^{2(S-1)} \frac{1+S}{2 S !}$$

For forbidden transitions,  $\Delta J = 1, 2, 3, \dots$ :

$$f = \frac{2 \pi}{9} (\alpha Z)^5 \frac{E_0^2 (\Delta J - 1 + E_0)^2}{1 \cdot 3 \cdot \dots \cdot (2 \Delta J - 1)^2 \Delta J} \times \left( \frac{E_n 2 \pi R}{hc} \right)^{2 \Delta J + 2} \left( \frac{2R}{a_K} \right)^{2(S-1)} \frac{1+S}{2 S !}$$

$\alpha$  = fine structure constant =  $1/137$ .

$Z$  = atomic number.

$E_n$  = energy given to neutrino.



$R$  = nuclear radius.

$a_K$  = Bohr radius of K shell.

$$S = (1 - \alpha Z^2)^{1/2}.$$

The probabilities of the first forbidden to the allowed transition will have a ratio of  $(\alpha Z/2)^2$ , and successive higher orders of forbiddenness will have probability ratios of  $(E_0/R)^2$ .

Observation of K capture is possible only through the detection of K X-radiation following absorption of a K electron. However, identification of K capture is sometimes hampered by a competing process of positron emission when this is followed by gamma radiation. If internal conversion of the gamma radiation is pronounced, the K-radiation is masked by similar radiation produced by the conversion. When positron emission is absent or when present but not accompanied by gamma radiation, K capture can be detected unambiguously. In some radioisotopes, the gamma radiation exhibits a much greater intensity than is expected from the observed positron activity. This, together with K-radiation readily establishes the existence of K capture.

## REFERENCES

1. Birge, R.T., Phys. Rev. 13, 233 (1941).
2. Handbuch der Physik XXIV:1, 519 (Berlin 1933).
3. Bethe and Heitler, Proc. Roy. Soc., 146, 83 (1934).
4. Evans, R.D., Seminar in Nuclear Science and Engineering, M.I.T. (1946).
5. Feather, , Camb. Phil. Soc. 34, 599 (1938).
6. Rutherford, E., Phil. Mag. 21, 669 (1911).
7. Mott, Proc. Roy. Soc. A135, 429 (1932).
8. Wentzel, Ann. d. Physik 69, 335 (1922).
9. Mott, N.F., Proc. Roy. Soc. 125, 222, 259 (1929). and Mott and Massy,
10. Theory of Atomic Collisions, Oxford (1933).
10. Fermi, E., Zeits. f. Physik 88, 161 (1934).
11. Siegborn, K., Proc. Roy. Soc. 189, 527 (1947).
12. Pollard, E. and Davidson, W.L., Applied Nuclear Physics, John Wiley and Sons, N.Y. (1942).
13. Kurie, Richardson, and Paxton, Phys. Rev. 49, 368 (1936).
14. Nordheim, L.W., and Yost, F.L., Phys. Rev. 51, 942 (1937).
15. Konapinski, E., Rev. Mod. Phys. 15, 209 (1943)
16. Wigner, Phys. Rev. 51, 106 (1937).
17. Gamow, G. and Teller, E., Phys. Rev. 49, 895 (1936).
18. Alvarez, L.W., Phys. Rev. 54, 486 (1938).
19. Bethe, H. and Bocher, R., Rev. Mod. Phys. 8, 55 (1936).

Table 3 . AVERAGE ENERGY OF BETA PARTICLES

The data given below are taken from the computed and compiled values for average beta energies reported by Marinelli, Brinckerhoff and Hine, Rev. Mod. Phys. 19, 25 (1947). To ensure the highest accuracy they computed average values only from magnetic spectrometer measurements reported after 1939. In the case of complex spectra, the average value of the components is given as well as the average for the total spectrum, which was determined from graphical analysis. The average for simple spectra was computed from Fermi's theory for the energy distribution by the formula

$$\bar{E} = \frac{\int_0^{E_0} E N dE}{\int_0^{E_0} N dE} \quad (\text{see: Beta Decay})$$

The column giving percentage indicates the per cent of only beta particles with different  $E_0$  or the per cent of positrons to K capture.

El.	Z	A	Rad.	T 1/2 days	%	$E_0$		$\bar{E}$		$\bar{E}_t$	
						mev	+	mev	kev	+	kev
C	6	11	$\beta^+$	.01415		0.97		.01			380 40
N	7	13	$\beta^+$	.00703		1.24		.02			475 45
Na	11	22	$\beta^+, K, \gamma$	1170.00	~100	.575		.03			225 20
Na	11	24	$\beta^-, \gamma$	.61		1.39		.005			540 20
P	15	32	$\beta^-$	14.5		1.712		.008			695 20
Cl	17	38	$\beta^-, \gamma$	.0259	53	4.94		.06	2230	90	
					11	2.79		.06	1190	40	1390 70
					36	1.19		.08	400	35	
K	19	40	$\beta^-, \gamma$	$5 \times 10^{11}$		1.35		.05			490 60
Sc	21	44	$\beta, \gamma$	.167	*	1.47		.02	645	35	
V	23	48	$\beta^+, K, \gamma$	16.	58	.715		.015			(300+25)(.58)

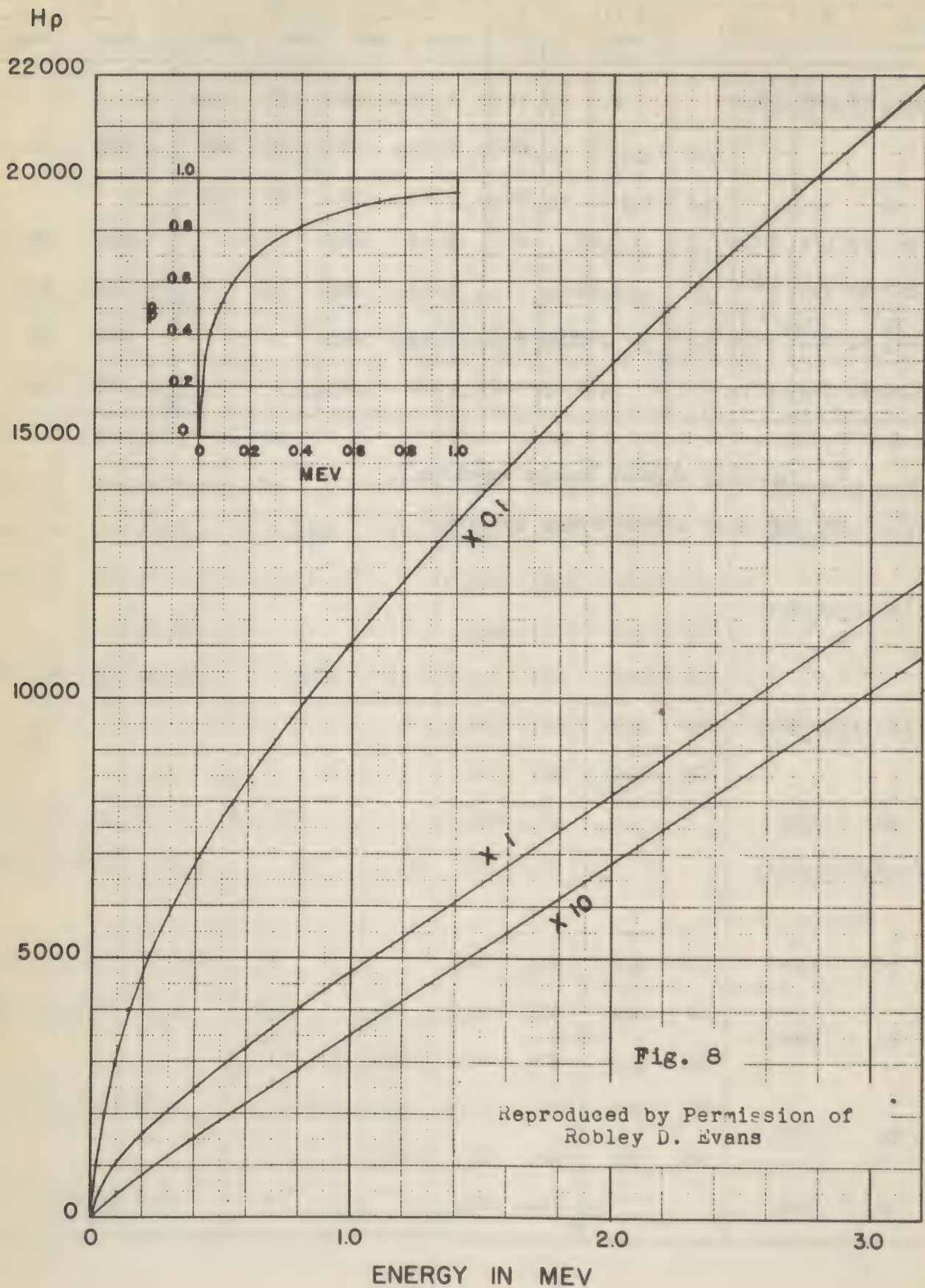


El.	Z	A	Rad.	T 1/2 days	%	E <sub>0</sub>		E		E <sub>t</sub>	
						mev	±    mev	kev	±    kev	kev	±    kev
Mn	25	52	β <sup>+</sup> ,K,γ	6.5	35	.58	.03			(240+20)(.35)	
Mn	25	56	β <sup>-</sup> ,γ	.108	50	2.81	.05	1240	50		
					30	1.04	.03	410	35	890	40
					20	.65	.1	280	25		
Fe	26	59	β <sup>-</sup> ,γ	47.	50	.46	.01	150	15		
					50	.255	.01	85	10	120	15
Co	27	55	β <sup>+</sup> ,K	.75		1.5	.05			515	90
Co	27	56	β <sup>+</sup> ,γ	85.		1.5	.05			655	35
Co	27	58	β <sup>+</sup> ,K,γ	65.	15	.47	.015			(195+20)(.15)	
Cu	29	61	β <sup>+</sup> ,K,γ	.142	78	1.23	.02			(555+40)(.78)	
Cu	29	64	β <sup>-</sup>	.53		.578	.003	175	30		
			β <sup>+</sup> ,K,γ	30	.659	.003	265	25	(205+30)(.58)		
Zn	30	63	β <sup>+</sup> ,K,γ	.0271	85	2.36	.04	1080	50		
					9	1.40	.04	615	30	(985+40)(.98)	
					4	.46	.03	180	20		
Br	35	82	β <sup>-</sup> ,γ	1.5		.465	.01			150	15
Cd	48	107	β <sup>+</sup> ,K,γ	.28	.31	.32	.01			(140+20)(.003)	
‡ 92											
In	49	114	β <sup>-</sup> ,(γ)	50		1.98	.03	765	30	940	30
Sb	51	124	β <sup>-</sup> ,γ	60	55	2.46	.07	980	40		
					45	.74	.03	260	25	660	35
I	53	130	β <sup>-</sup> ,γ	.525	45	1.03	.02	360	20		
					55	.61	.03	195	20	270	20
I	53	131	β <sup>-</sup> ,γ	8.		.595	.01			205	20

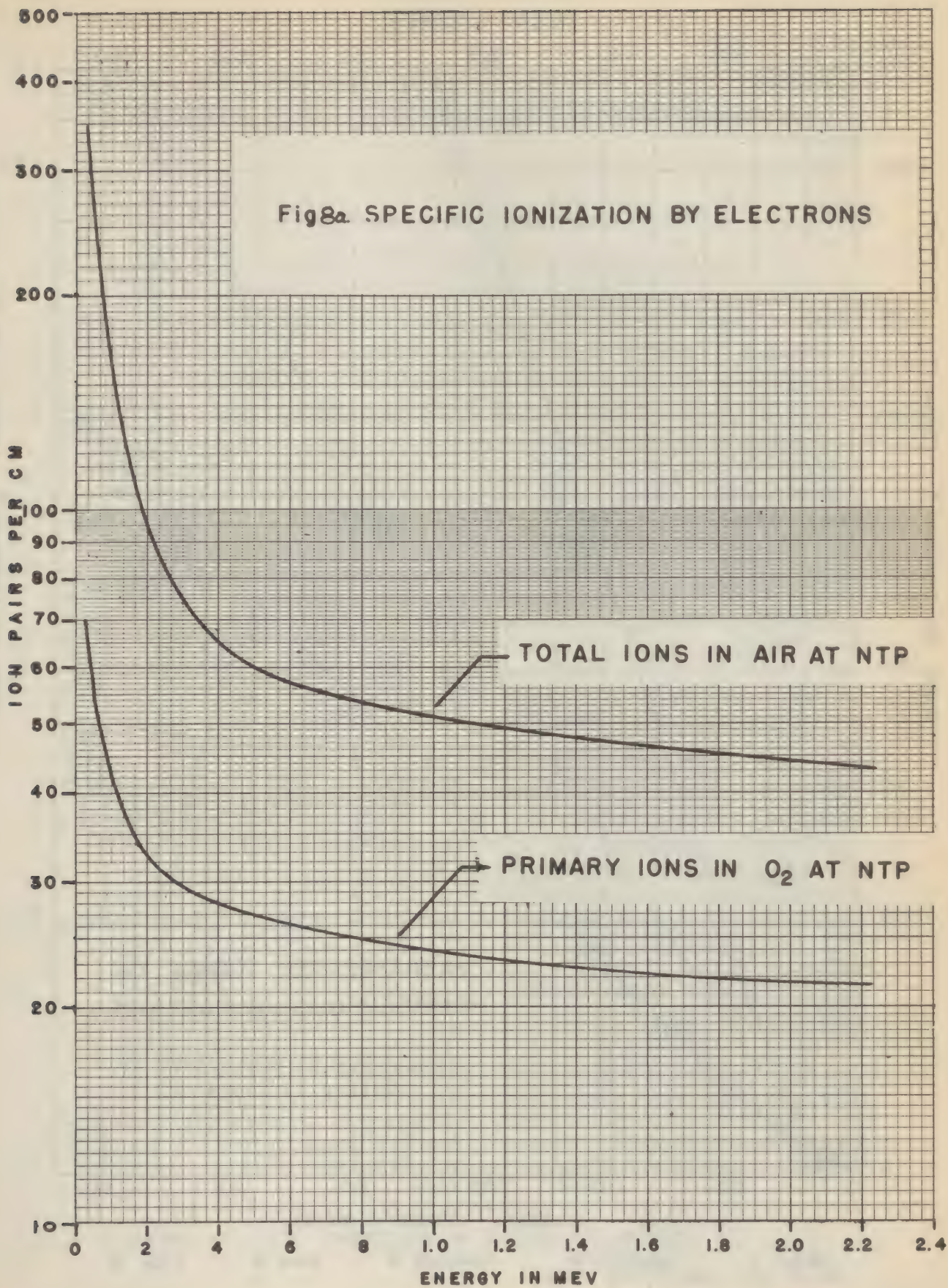
El. Z A	Rad.	T 1/2 days	%	E <sub>0</sub>		E		E <sub>t</sub>	
				mev	± mev	kev	± kev	kev	± kev
La 57 140	β <sup>-</sup> , γ	8.	12	2.12	.08	835	60		
			60	1.40	.04	510	40	495	40
			28	.90	.03	320	30		
Ir 77 194	β <sup>-</sup> , γ	.81	*	2.18	.04			835	50
RaE 83 210	β <sup>-</sup>	4.85		1.17	.005			330	10
UX <sub>2</sub> 91 234	β <sup>-</sup> , γ	.00079	*	2.32	.005			865	50
UZ 91 234	β <sup>-</sup> , γ	.28	**90	.45	.03			150	20

\* for only highest energy spectrum

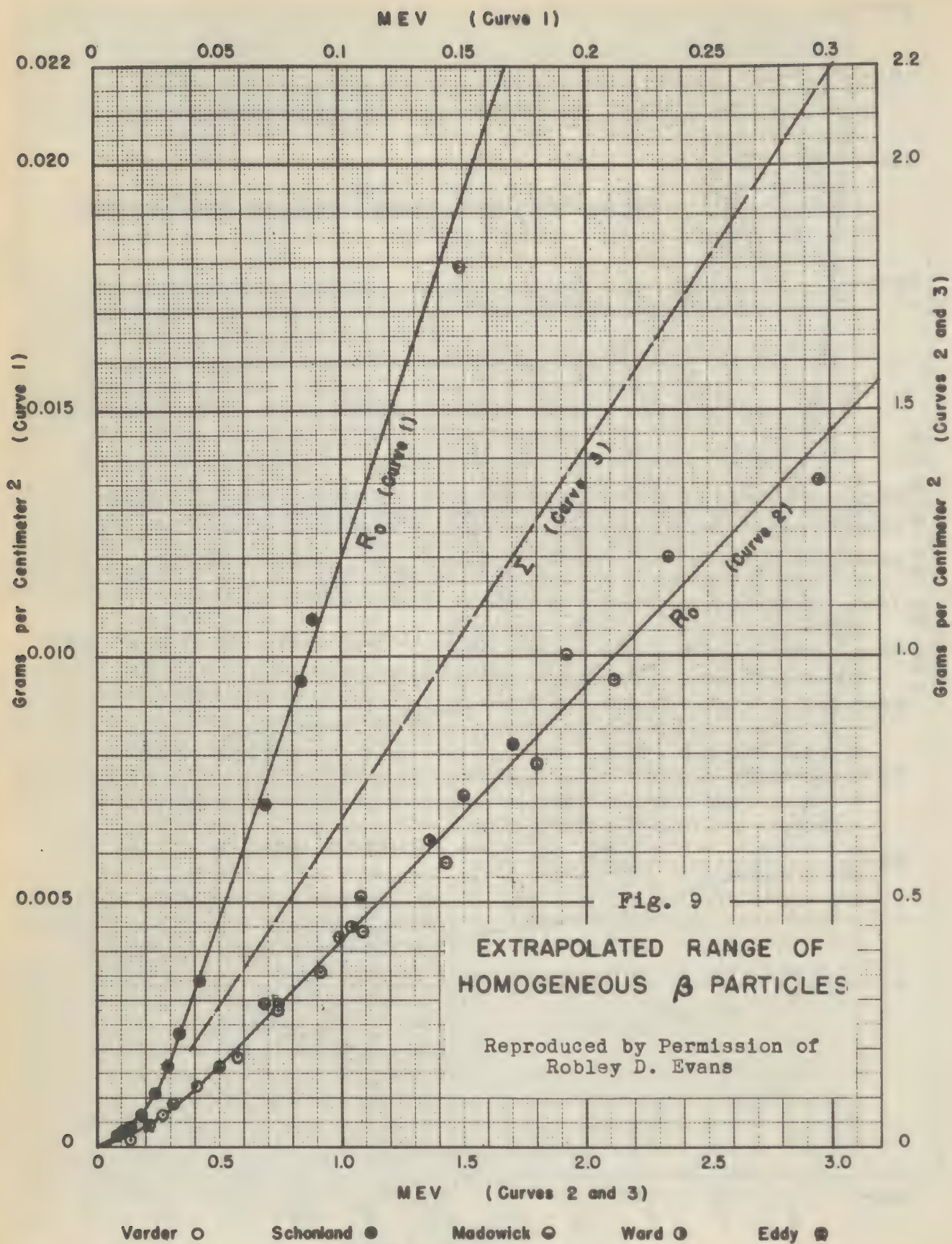
\*\* for only lowest energy spectrum











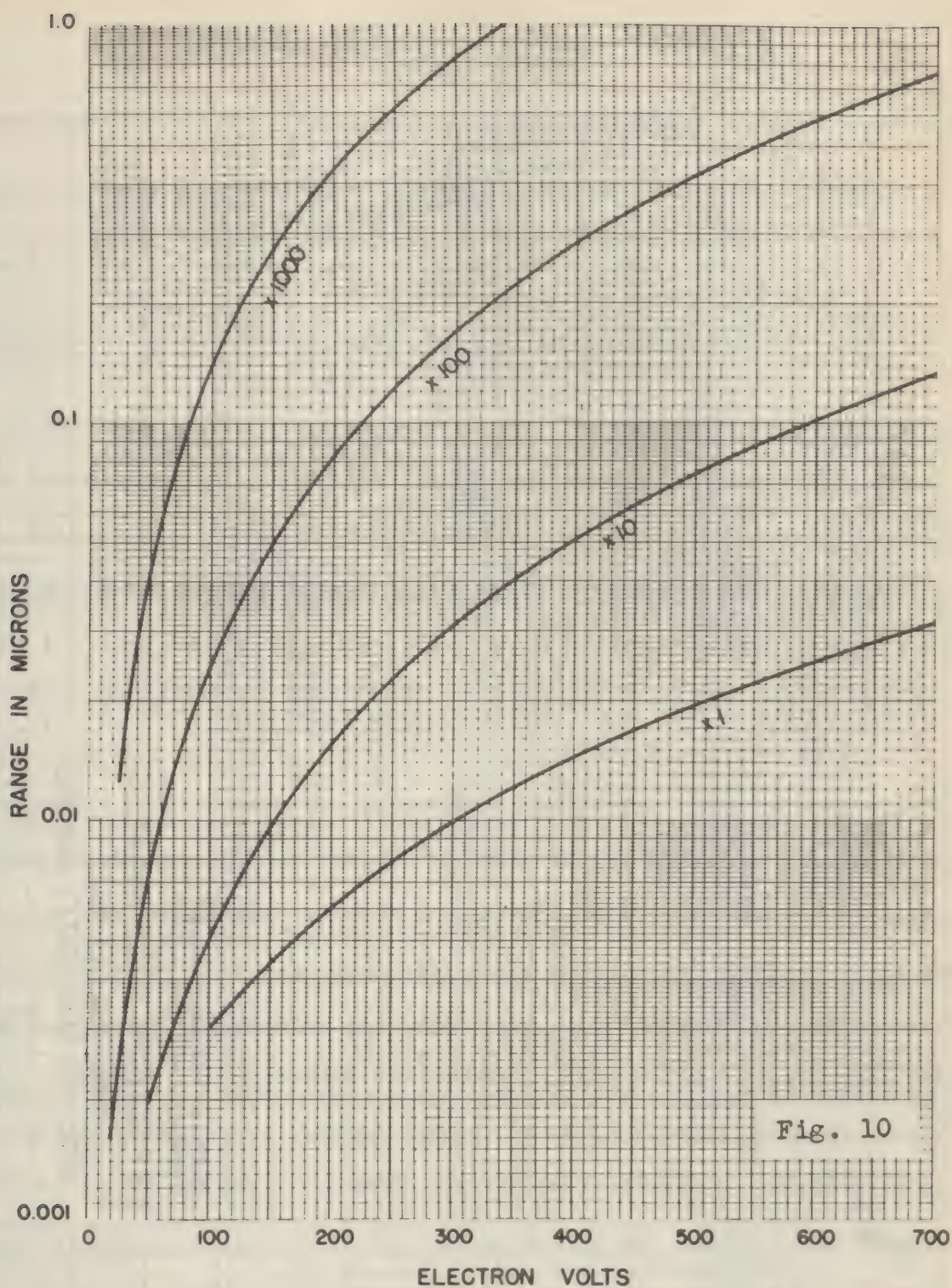
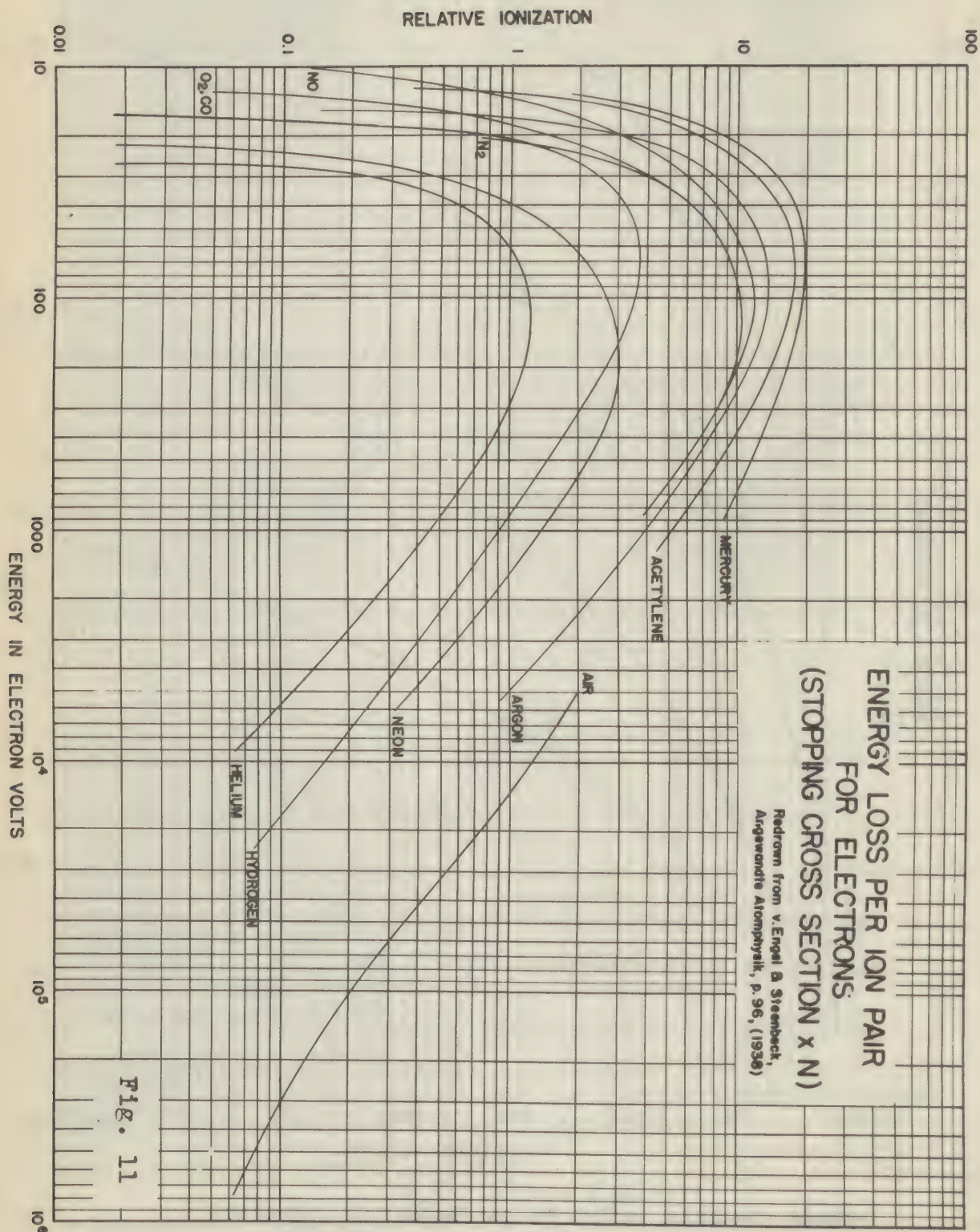


Fig. 10

RANGE OF BETA PARTICLES IN TISSUE OF DENSITY = 1

WILLIAMS, PROC. ROY. SOC., A132, 310 (1930)





#### 4. ALPHA PARTICLE

##### A. Physical Properties

Mass -----4.00390 0.00003

Spin -----0

Magnetic moment--

Packing Fraction--0.00098 mass units

Binding energy----30.0 mev

On the basis of the existence rules for stable nuclei, the alpha particle is representative of the most stable configuration of neutrons and protons. This is also immediately apparent from its comparatively high binding energy of 7.5 mev per nucleon, indicating that the short range nuclear forces binding the four particles are very nearly saturated. It can be safely assumed from this, that in the unexcited alpha particle, the proton and neutron of each pair are to be found in the same state except for their spin and that both pairs occupy the lowest quantum levels. This is borne out by the relative instability of nuclei formed by adding to or subtracting from the helium nucleus either a proton or neutron and also of nuclei containing four particles but different combinations of protons and neutrons. All such nuclei are either radioactive or, if stable, exhibit markedly smaller binding energy. Further, the electrostatic repulsion, which in heavier nuclei tends to decrease the effective binding energy, is in this instance quite small.

It is to be expected, however, that additional quantum levels will exist corresponding to several states of excitation and evidence for their existence has been indicated in the energy region of 10 - 20 mev (1). Calculations by Feenberg (2) and Bethe (3) lead to the possible existence of a  $1p$



state at something less than 20 mev above the normal level, and two  $^3P$  states, one below the  $^1P$  state and the other above it and probably not stable. From the optical selection rules for such states, it was suggested that three gamma rays should be observed corresponding to the allowed transitions  $^1P - ^1S$ ,  $^3P - ^1S$  and  $^1P - ^1D$ . On the basis of rather inconclusive experimental results, these transitions have been tentatively identified with gamma energies of approximately 16, 10, and 6 mev respectively.

### B. Absorption of Alpha Particles

The mechanism mainly responsible for the absorption of not only alpha particles but all other heavy charged particles is the interaction of their coulomb fields with the bound electrons of the absorbing material. The rate of energy loss is adequately accounted for by the transfer of small fractions of the particles kinetic energy and momentum to the excitation and ionization of each atom of the absorber within a radial distance of roughly  $2v/w$  from its path, where  $v$  is the particles velocity and  $w$ , the lowest electron vibrational frequency of an absorbing atom. Two other absorbing processes occur, namely nuclear interaction and scattering by atomic nuclei, but their contribution to the absorption of a beam of heavy particles is negligible.

Assuming that the stopping of heavy charged particles results wholly from ionization and excitation, calculations of the rate of energy loss,  $-dE/dx$ , in simple substance compare remarkably well with values derived from accurately measured ranges of alpha particles from the natural radioactive elements. The expression for energy loss per cm path, derived by Bethe (4,5,6) and Møller (7), is applicable to mesons, protons, deuterons and alpha particles over a wide range



of energies. In its general form, including the relativity effect, it is given as:

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 ZN}{m v^2} \left[ \log \frac{2m v^2}{I(1-\beta^2)} - \beta^2 \right] - C_K$$

$e$  = electron charge.

$m$  = electron mass.

$N$  = number of atoms (not molecules) per cc.

$z$  = charge of particle ( $z = 2$  for alphas).

$Z$  = Atomic number of absorber.

$v$  = velocity of particle.

$\beta$  =  $v/c$ .

$I$  = average ionization potential.

$C_K$  = K electron correction term.

The range in energy over which the energy loss formula remains valid is determined by the lower and upper limits inherent in its derivation. Beyond this, other effects become important which cannot be accounted for solely by ionization losses. The lower limit arises from the assumption that the particle velocity is greater than the highest electron orbital velocity in an absorbing atom, i.e.,  $E \gg M/mE_K$ , where  $E_K$  is the K electron ionization potential. When the particle and electron velocities become comparable, the probability of electron capture is no longer negligible and the charge of the particle is indeterminate in that it fluctuates with each collision; either gaining or losing an electron until it has been brought to rest. Considerable error is introduced in attempting to calculate energy loss for protons with less than 0.1 mev and

alpha particles less than 1.0 mev.

The upper limit of validity requires that the particle energy,  $E$ , be small compared to  $M^2 c^2/m$ . At sufficiently high energies, radiative loss becomes important. Even at energies of the order of 2000 mev a correction is required to particles traversing dielectric absorbers (see Fermi effect).

When the velocity is small compared to the velocity of light,  $\beta \ll 1$ , the relativistic terms can be neglected. If, in addition  $\eta \ll 1$  (see below), the K electron term is negligible and the energy loss formula takes the simple form:

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2 Z N}{m v^2} \log \frac{2mv^2}{I}$$

### C. Average Ionization Potential

The average ionization potential,  $I$ , of an absorbing nucleus appears to be constant for all incident heavy particles and energies but increases with atomic number. As yet no satisfactory means for its calculation has been provided (4, 6). Its value, however, can be determined empirically by adjusting the calculated range energy curve (see Range) to an accurately known range and energy of a proton or alpha particle in the absorber using  $I$  as an arbitrary parameter (6,8,9,10). The best theoretical value is given by Bloch's equation (11),  $I \sim Z$ , using Wheeler's constant of proportionality of 11.5. The values of  $I$  determined empirically by Mano (12) and those calculated from the Bloch-Wheeler equation are listed below:

Table 4 . AVERAGE IONIZATION POTENTIALS

Absor- ber	Z	I ev (Mano)	I ev (Wheeler)	Absor- ber	Z	I ev (Mano)	I ev (Wheeler)
1/2 H <sub>2</sub>	1	16.0	11.5	Cu	29	320	333.5
		17.5	23.0	Zn	30	340	345.
He	2	34.5		Kr	36	390	414.
		44		Mo	42	445	483.
Li	3	38	34.5	Pd	46	490	529.
1/2 N <sub>2</sub>	7	81	80.5	Ag	47	490	540.5
air	7.23	87	83.15	Cd	48	495	552.
		80.5 (6)		Sn	50	500	575.
		98.1 (13)		Xe	54	530	621.
1/2 O <sub>2</sub>	8	99	92.0	P	78	790	897.
Ne	10	132	115.0	Au	79	780	908.5
Al	13	155	149.5	Pb	82	800	943.
A	18	195	207.0				
Ni	28	325	322.				

D. Correction Terms

The K electron correction term added by Bethe to the stopping formula takes into account the reduced contribution of the K electrons to the stopping power due to the screening effects of the outer electrons in all but the lightest elements. Its value as given by Livingston and Bethe (6) is plotted in Fig. (14) as a function of  $1/\eta$  where

$$\frac{1}{\eta} = \frac{2(Z - 0.3) R_y}{m v^2}$$



$Z - 0.3$  = effective atomic number.

$R_y$  = Rydberg constant for hydrogen.

$m$  = electron mass.

$v$  = velocity of particle.

For energies above several mev the correction becomes negligible and for energies very much smaller than this, where it assumes an appreciable magnitude, the effect of electron capture and loss results in an error of even greater magnitude and the formula breaks down. The term, therefore, is frequently omitted in calculations since it does not provide sufficient correction at low energies and is negligible at higher energies.

A correction of a similar nature can be made in the effective atomic number. In all but the lightest elements, ( $Z > 7$ ), the K and L and in the heavier elements, possibly also the M and N, electrons are little excited because of the strong screening effect and do not contribute one charge unit per electron to the value of  $Z$  used in the formula. The effective fractional contribution to  $Z$  per K and L electron is plotted in figure 13 from calculations by Hönig (14). At the present time it is not known to what extent this correction is important but it should be negligible at high energies. It is, in effect, similar to the procedure followed by Duncanson (9) in treating both  $I$  and  $Z$  as parameters in adjusting the simple Bethe energy loss formula to the observed data.

An important correction to the Bethe stopping formula was introduced by Fermi (15) for very high energy particles traversing polarizable media. The electric field of the particle is altered by local polarization of the absorber leading to a lower rate of energy loss as compared with the formula above. The energy loss formula is then:

1. For  $v < c/\sqrt{\epsilon}$

$$\frac{dE}{dx} = \frac{2\pi e^4 Z^2 N}{mv^2} \left[ \log \frac{mv^2}{I} + \log \frac{\epsilon - 1}{\epsilon(1 - \beta^2)} - \beta^2 \right]$$

2. For  $v > c/\sqrt{\epsilon}$

$$-\frac{dE}{dx} = \frac{2\pi e^4 z^2 Z N}{m v^2} \left[ \log \frac{2 m v^2}{I} - \frac{1 - \beta^2}{\epsilon - 1} \right]$$

$\epsilon$  = di-electric constant

If the absorbing medium can be assumed to consist of elementary oscillators with a natural frequency,  $w_0$ , the di-electric constant is a function of the electric field frequency,  $w$ , of the incident particle and is given by the expression:

$$\epsilon = 1 + \frac{4\pi e^2 Z N}{m(w_0^2 - w^2)}$$

where  $4\pi NZe^2/m$  is the plasma frequency.

The correction becomes appreciable for protons of the order of 1000 mev and alpha particles at slightly higher energies. But for electrons and mesons, it is an important factor at only several hundred mev.

#### E. Relative Stopping Power.

The energy loss per cm is usually referred to as the stopping power of a substance. Calculations of the stopping power of various substances relative to air, for which accurate calculations and measurements have been made, is complicated by the dependence on the velocity of the particle as well as on the atomic number and average ionization potential. Approximately, it is given by:

$$S = \frac{N'Z' \log 2mv^2/I'}{NZ \log 2mv^2/I}$$

where the primed letters refer to the substance and the unprimed to air. Measurements of relative stopping powers of absorbers for alpha particles relative to air are given below for two energies and in figure 15 for various energies.

For heavy charged particles with energy above one mev the relative stopping power changes very slowly while above 10 mev it remains essentially constant for all higher energies.

Table 5.

ATOMIC STOPPING POWER FOR ALPHA PARTICLES RELATIVE TO AIR AT N.T.P.

Absor- ber	RaC $\alpha$ (16)	6 mev $\alpha$ (10)	Absor- ber	RaC $\alpha$ (16)	6 mev $\alpha$ (10)
H	.200	.20	Ni	1.89	
He	.308	.35	Cu	2.00	2.57
Li	.519	.50	Zn	2.05	
Be	.750		Br	2.51	
C	.814		Kr		2.92
N	.939	.99	Mo		3.20
O	1.000	1.07	Ag	2.74	3.36
Ne		1.23	Cd	2.75	
Mg	1.23		Sn	2.86	3.59
Al	1.27	1.5	I	3.55	
Si	1.23		Ye		3.76
Cl	1.76		Pt	3.64	
A	1.80	1.94	Au	3.73	4.50
Ca	1.69		Tl	3.76	
Fe	1.96		Pb	3.86	4.43



### F. Atomic Stopping Power

The atomic stopping power,  $\sigma$ , frequently termed stopping cross section, is defined as the energy loss per cm divided by the number of atoms per cc. Using the approximate form of the energy loss formula, it is given by:

$$\sigma = \frac{4\pi e^4 z^2 Z}{m v^2} \log \frac{2 m v^2}{I} \quad \text{ev cm}^2$$

### G. Mass Stopping Power

The mass stopping power is defined as the energy loss per cm divided by the density of the absorber or as the stopper power per unit density. From Baggs empirical rule as well as from the stopping power formula, it is found to vary approximately as the inverse square root of the atomic mass of the absorber.

### H. Range of Particles

The distance traversed by a charged particle in an absorber is the total path length required for complete loss of the particles energy. With an initial energy  $E_0$ , in units of  $Mc^2$ , the range is calculated with the aid of the energy loss formula by the integral

$$R = \int_0^{E_0} \frac{dE}{-\frac{dE}{dx}}$$

$$-\frac{dE}{dx} = \text{energy loss per unit length of path.}$$

The evaluation of the integral must be carried out numerically and when possible, is usually started at some well established experimental value of the

range and energy rather than that at zero energy.

Unlike the comparatively indeterminate range of beta particles and the exponential absorption of gamma rays, the ranges of mesons, protons, deuterons, and alpha particles are well defined in that all particles in an initially homogeneous beam are brought to rest after traversing the same distance through an absorber with only a small spread about the mean range. Heavier particles with a higher charge number, such as fission fragments do not exhibit well defined ranges. Their charge varies rapidly with velocity due to electron capture and hence the stopping formula cannot be applied even for a first approximation. It is probable, however, that at energies of the order of 1,000 mev their charge will remain constant and their velocity become high enough to satisfy the conditions required by the formula. This will still not prove to be very useful, since the range of a heavily charged particle is small and the straggling large.

On the basis of early measurements on the range of alpha particles from the natural radioisotopes, three empirical relations were established for the variation of range in air with energy.

1. Range between 0 - 3 cm:

$$R \sim v^{3/2} \sim E^{3/4}$$

2. Range between 3 - 7 cm (Geiger formula):

$$R = 9.67 \times 10^{-28} v^3$$

3. Range above 7 cm:

$$R \sim v^4 \sim E^2$$

These relations should be regarded only as qualitative since, in the variation of  $R$  with  $v^n$ , the exponent  $n$  also depends on the velocity and increases from

$n = 1.4$  for low velocities to  $n = 4.0$  for very high velocities (6).

The relative range of a particle in a substance compared to air cannot be calculated with accuracy by a simple expression because of the involved dependence on the stopping power of different atoms. Nevertheless, a rough estimate of the range of alpha particles in substances other than air can be calculated from Geiger's formula:

$$R = 3.2 \times 10^{-4} \frac{R_0 \sqrt{A}}{\rho}$$

$R_0$  = range in air.

$\rho$  = density of absorber.

$A$  = average atomic weight of absorber.

Table 6. RANGES OF RAC ALPHA PARTICLES IN VARIOUS SUBSTANCES (16)

Substance Range x 10 <sup>-3</sup> cm		Substance Range x 10 <sup>-3</sup> cm	
Li	12.91	Ag	1.92
Mg	5.78	Cd	2.42
Al	4.06	Sn	2.94
Ca	7.88	Pt	1.28
Fe	1.87	Au	1.40
Ni	1.84	Tl	2.33
Cu	1.83	Pb	2.41
Zn	2.28		

### I. Specific Ionization

The number of ion pairs formed per unit length of path of an alpha particle is referred to as the specific ionization. Its value depends upon the absorbing material and on the velocity and charge of the particle at any instant.



In air at normal temperature and pressure, the specific ionization remains essentially constant with a value of 2000 ion pairs per cm for high energy alpha particles. At low energies, it increases rapidly to a maximum of 6000 ion pairs for an energy corresponding to a residual range of approximately 0.4 cm as shown in figure 16.

### J. Delta Rays

The recoil electrons produced by alpha particles, observed as short, faint straggling tracks branching from the alpha track in a Wilson cloud chamber, are referred to as delta rays after J. J. Thomson (17). The maximum energy imparted to a recoil electron, which occurs in a head-on collision, corresponds to twice the alpha particle velocity or  $E_{\max} = 2mv^2 = 4mE/M$ . Thus, for a 10 mev alpha particle the most energetic delta ray will have an energy of approximately 6300 ev and a range in air of several mm. The average number of ion pairs liberated by a delta particle of energy  $E_\delta$  has been calculated to be (18):

$$n = 3/4 \left( 1 + \frac{E_\delta}{V} \right)$$

$V$  = ionization potential of absorber.

The number of delta rays produced and their energy distribution depends in a complicated way on the alpha particle velocity and the absorber, and no satisfactory method for their calculation is available. Experimental data is given in table 7.

## K. Straggling of Alpha Particles

The range of energetically homogeneous alpha particles exhibit a statistical fluctuation or "straggling" about an average value. Two factors are mainly responsible for straggling: 1. fluctuation in the number of ions produced per unit length, particularly near the end of the range where the charge of the alpha particle may fluctuate; 2. statistical variation in the energy loss per ion pair. By plotting the number of alpha particles of initially homogeneous energy against the observed range, an integral range distribution curve is obtained (see figure 17). Differentiating this curve results in a differential range distribution curve or the distribution of ranges about an average value which is approximately a Gaussian distribution curve due to the purely statistical nature of straggling.

The mean range is defined as the range corresponding to the maximum of the differential (Gaussian curve) or alternatively as the range at which the number of alpha particles is reduced by one-half.

An extrapolated range is determined from the integral curve by extending a straight line along the slope of steepest descent to where it intersects the abscissa (range). From the difference between the extrapolated range,  $R$ , and the mean range,  $R_0$ , given by  $S^2 = 1/2 \int (R-R_0)^2$ , the Gaussian (differential) distribution can be expressed as:

$$P dR = \frac{1}{2S} e^{-\frac{\pi}{4S^2}(R-R_0)^2} dR$$

These definitions are exactly true only for energetically homogeneous particle beams i.e., particles from a source which is infinitesimal in thickness. In practice, sources and targets are usually "thick", i.e., thicker than the range of the particles. In this case the beam is not strictly homogeneous because



particles emitted by atoms at various depths are partially absorbed and scattered by different amounts before reaching the surface of the source. However, from thick, homogeneous samples and thick targets in which the production of particles is uniform through the thickness of target, the extrapolated range obtained from the measured number-range curve gives the mean range of the particles coming from the surface (6). Corrections must be applied in all other cases, e.g. "semi-thick" targets and sources (i.e., with a thickness of the order of the particle range) and in thick targets when the radiation producing the particles does not penetrate the target with uniform intensity.

#### L. Scattering of Alpha Particles

Elastic scattering of heavy charged particles is quantitatively accounted for on the basis of interaction between the Coulomb fields of the incident particle of charge  $ze$  and the struck nucleus of charge  $Ze$ . It is assumed in such collisions that the particle does not approach the nucleus so close as to be affected by the short range nuclear forces since these fields result in a different kind of scattering. For alpha particles, the minimum collision distance appears to be approximately  $2.05 \times 10^{-13} A^{1/3}$  where  $A$  is the atomic number of the struck nucleus.

The simplest scattering occurs in collisions of particles with very heavy nuclei since the struck nucleus then remains virtually stationary during the collision and the particle is deflected, or recoils, with little loss of energy and momentum. Rutherford's formula expressing the number of particles deflected into a unit solid angle at an angle  $\theta$  with the initial direction is then:

$$n(\theta) = n_0 N \left( \frac{e^2 z Z}{2 m v^2} \right)^2 \operatorname{cosec}^4 \frac{\theta}{2}$$



$n_0$  = initial number of particles in the beam.

$N$  = number of atoms per cc.

$z$  = charge number of particle.

$Z$  = atomic number of scatterer.

$m$  = mass of particle.

Collisions of alpha particles with light nuclei must be corrected for the contribution of energy to the struck nucleus which recoils with an appreciable fraction of the total energy. The general Rutherford formula for the number,  $n$ , of particles scattered into a unit solid angle at an angle,  $\theta$ , is:

$$n(\theta) = n_0 N \left( \frac{e^2 z Z}{m v^2} \right)^2 \operatorname{cosec}^3 \theta \frac{\left[ \cot \theta \pm \sqrt{\operatorname{cosec}^2 \theta - \left( \frac{m}{M} \right)^2} \right]^2}{\sqrt{\operatorname{cosec}^2 \theta - \left( \frac{m}{M} \right)^2}}$$

$M$  = mass of nucleus.

where the + sign is used if  $M > m$ , and - sign if  $M < m$ .

Although particles will be scattered at all directions, the intensity drops off very rapidly with the angle, thus in the case of alpha particles on platinum, less than one particle in 8000 will be scattered into an angle greater than  $90^\circ$ . Backscattering in light elements is entirely negligible. Calculation of the scattering of particles by heavy elements for energies up to 10 mev are given to a high degree of accuracy by the Rutherford formulae.

Deviations from Rutherford (Coulomb) scattering calculated from the formulae above will be found for certain energies of the incident alpha particle depending upon the properties of the scattering nucleus. Anomalous scattering will occur if, 1. the particle energy is sufficiently high to penetrate the electrostatic potential barrier and be affected by the nuclear forces; 2. the energy of the particle plus the internal energy of the scattering nucleus equals the energy of a quantum state of the compound nucleus. Anomalous

scattering which increases slowly with increased particle energy can usually be identified with penetration of the potential barrier. Anamolous scattering which increases rapidly to a maximum intensity and then decreases, indicates resonance scattering.

### M. Alpha Decay

The theory of alpha decay is based on the now familiar quantum mechanical problem of the penetration of charged particles through potential barriers. Some assumptions must be made about the shape of the potential field forming the barrier, but the theory can account for the main details of alpha emission and provide estimates of its probability.

If it is assumed that the alpha particles already exists as a separate entity within the nucleus and that the only effect of the remaining particles on it is to provide a potential "well" in which the alpha particle exists in some energy state, the problem immediately reduces to the one-body model for alpha decay (19,20).

Within the nucleus the alpha particle can move with relative freedom. At the surface it is constrained from leaving by an effective surface tension maintained by the unsaturated attractive nuclear forces of those particles lying at the surface. This force rises rapidly to a maximum value at a distance approximately equal to the nuclear radius and for the purpose of calculations it is usually regarded as vertical at the nuclear radius and flat within the nucleus. Outside the nucleus, the nuclear potential field decreases rapidly and only the repulsive Coulomb field remains which decreases more slowly, i.e., as  $1/r$  from the center of the nucleus. The height of the barrier above the zero Coulomb energy, i.e., the value approached asymptotically by the Coulomb field, is determined by the point near the



surface where the attractive and repulsive fields are equal for the alpha particle. This is approximately the magnitude of the coulomb field at the surface or

$$E_b = \frac{e^2 z Z}{R}$$

$z$  = alpha charge.

$Z$  = atomic number.

$R$  = nuclear radius.

The field in the nucleus, therefore, may be represented by a cylindrical potential hole extending an unknown distance  $E_0$  below the zero coulomb energy and  $E_b$  above. Outside, and starting from the top of the cylinder, only the coulomb field is effective.

In the nucleus, an alpha particle in an energy state above the zero coulomb energy has a finite probability of leaving by penetration through the barrier even though its energy is considerably less than the barrier height. If it is raised to a level equal to the barrier, or into the continuum of states above the barrier by external excitation, it is emitted, to all purposes instantaneously. The mean life,  $\tau$ , for alpha emission by penetration through the potential barrier (alpha decay) is given by the expression:

$$\tau = \tau_0 e^f$$

$$\tau_0 = \frac{2 \left( 2 M^3 R^5 (zZe^2 - RE) \right)^{1/2}}{h^2} \approx 10^{-21} \text{ sec.}$$

$$f = \frac{8\pi zZe^2}{hv} \left( \cos^{-1} x^{1/2} - x^{1/2} (1-x)^{1/2} \right)$$

$$\approx \frac{\pi zZe^2}{hv} - \frac{4\pi e}{h} (2 zZ MR)^{1/2}$$



$$X = \frac{ER}{zZe^2}$$

$E$  = energy of alpha particle above zero coulomb energy, or the observed kinetic energy of the alpha plus the recoil nucleus.

$m$  = mass of alpha particle.

$R$  = nuclear radius.

$v$  = alpha particle velocity.

$h$  = Planck's constant.

The factor  $\tau_0$ , is the mean life for alpha emission in the absence of a barrier and  $1/e^f$  is the transmission coefficient or penetrability factor of the barrier.

Writing the expression for  $\tau$  in terms of logarithms,

$$\log \tau = \frac{A}{v} + B$$

$$\frac{A}{v} = f$$

$$B = \log \tau_0$$

If it is assumed the nuclear radius is nearly constant for all alpha emitters,  $A$ , and  $B$  are nearly constant and the logarithm of the mean life is inversely proportional to the velocity of the alpha particle. This relation was first discovered empirically by Geiger and Nuttall (21). A similar relation is found between the range,  $R$ , and the mean life:

$$\log \tau = C - D \log R$$

A modification of the one-body theory of alpha decay has been proposed (22) in which it is assumed that the alpha particles does not exist in the

nucleus as a separate entity but rather, its constituent particles are bound in the general structure of the remaining particles. The probability of alpha emission is then determined by the probability that an alpha particle is formed as well as by the probability for barrier penetration. The mean life for alpha emission will be then

$$\tau = \tau_0 e^f \frac{h}{2\pi G}$$

where  $e^f$  is the penetrability and  $h/2\pi G$  is the probability of alpha particle formation. The many-body model, as it is called, leads to a lower barrier height, and a somewhat larger nuclear radius ( $\sim 13 \times 10^{-13}$  cm as compared to  $\sim 8.5 \times 10^{-13}$  cm for the one-body model).

## REFERENCES

1. Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. 48, 484 (1935).
2. Feenberg, Phys. Rev., 49, 328 (1936).
3. Bethe, H., and Bacher, R.F., Rev. Mod. Phys. 8, 82 (1936).
4. Bethe, H., Ann. d. Physik 5, 325 (1930).
5. Bethe, H., Zeits. f. Physik 76, 293 (1932).
6. Livingston, S. and Bethe, H., Rev. Mod. Phys. 9, 263 (1937).
7. Moller, Ann. d. Physik 14, 531 (1932).
8. Blackett, Proc. Roy. Soc. 135, 132 (1932).
9. Duncanson, Proc. Camb. Phil. Soc. 30, 102 (1934).
10. Manno, Ann. d. Physik 1, 407 (1934).
11. Bloch, F., Zeits, F. Physik 81, 363 (1933).
12. Mano, Annal. de Phys. 1, 446 (1934).
13. Chicago Group.
14. Honl, H., Zeits, f. Physik 84, 1 (1933).
15. Fermi, E., Phys. Rev. 57, 485 (1940).
16. von Taubenburg, Zeits. f. Physik 2, 268 (1920).
17. Thomson, J.J., Camb. Phil. Soc. 13, 49 (1904).
18. Fowler, R.H., Proc. Camb. Phil. Soc. 21, 531 (1923).
19. Gamow, Zeits. f. Phys. 52, 510 (1929).
20. Condon, and Gurney, Phys. Rev. 33, 127 (1929).
21. Geiger and Nuttal, Camb. Phil. Mag. 22, 613 (1911).
22. Bethe, Phys. Rev. 50, 977 (1936).

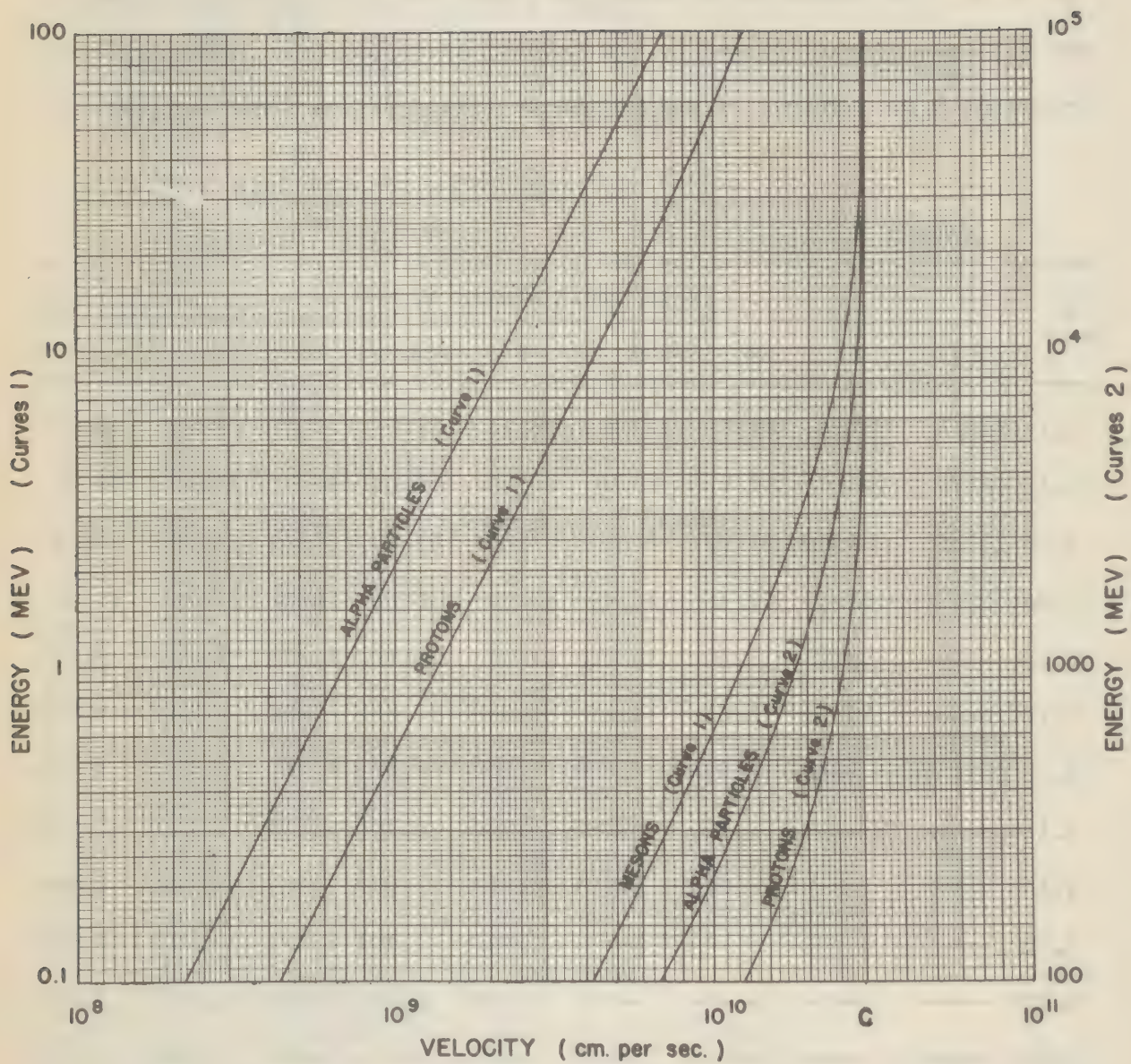


Table 7. Secondary Electron Produced by Alpha Particles in Tissue

Table gives the number of electrons, with an energy greater than E, produced by an alpha particle per micron path length in tissue of density.

$\rho = 1$ . The values for similar substances but with different densities are obtained by multiplying by the density in gm per cc.<sup>2</sup> Data reprinted from Lea, D.E., Actions of Radiations on Living Cells, Cambridge (1947).

E mev	a-particle energy in mev								
	1	2	3	4	5	6	7	8	10
0.1	416.4	231.4	159.5	121.5	98.15	82.31	70.87	62.22	50.01
0.15	246.6	146.6	102.9	79.08	64.20	54.01	46.61	40.99	33.03
0.25	110.8	78.64	57.59	45.13	37.03	31.38	27.21	24.02	19.44
0.45	20.26	33.36	27.40	22.49	18.92	16.28	14.27	12.70	10.39
0.65	-----	15.95	15.80	13.78	11.96	10.48	9.298	8.343	6.907
0.75	-----	10.72	12.31	11.17	9.865	8.737	7.805	7.037	5.862
0.95	-----	3.575	7.546	7.596	7.006	6.354	5.763	5.250	4.432
1.1	-----	-----	5.109	5.768	5.544	5.136	4.718	4.336	3.701
1.5	-----	-----	0.993	2.681	3.074	3.078	2.954	2.793	2.466
2.25	-----	-----	-----	-----	0.810	1.191	1.337	1.378	1.334
3.25	-----	-----	-----	-----	-----	0.031	0.342	0.507	0.638
4.25	-----	-----	-----	-----	-----	-----	-----	0.046	0.269

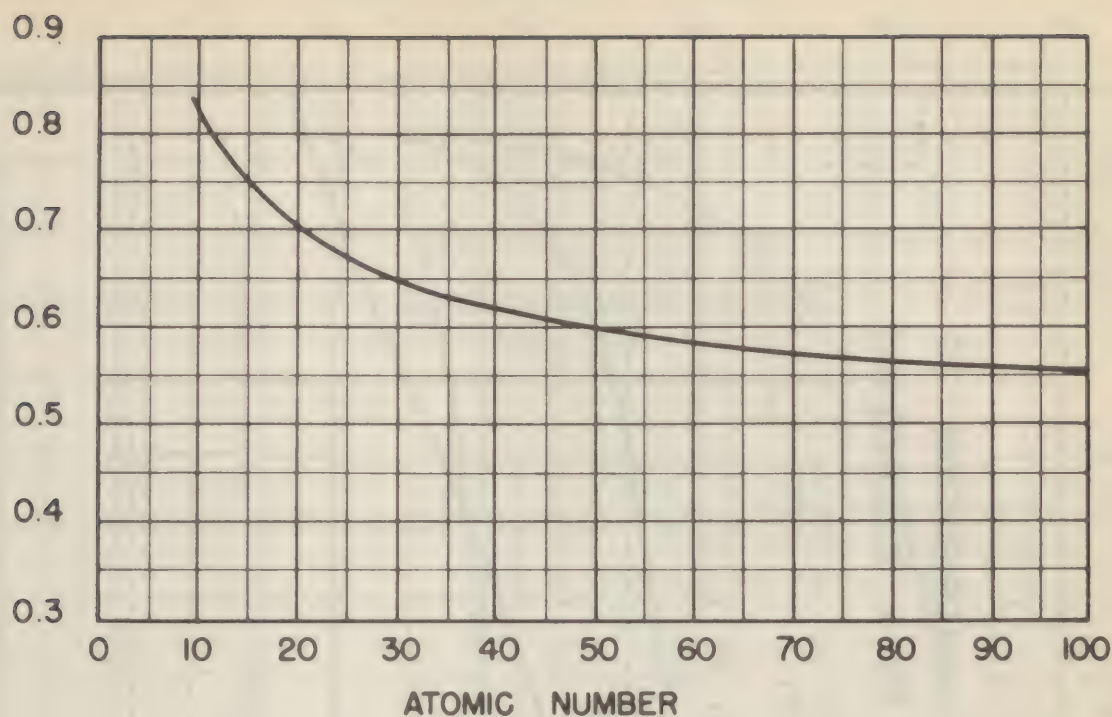


ENERGY-VELOCITY CURVES FOR ALPHA PARTICLES, PROTONS,  
AND MESONS

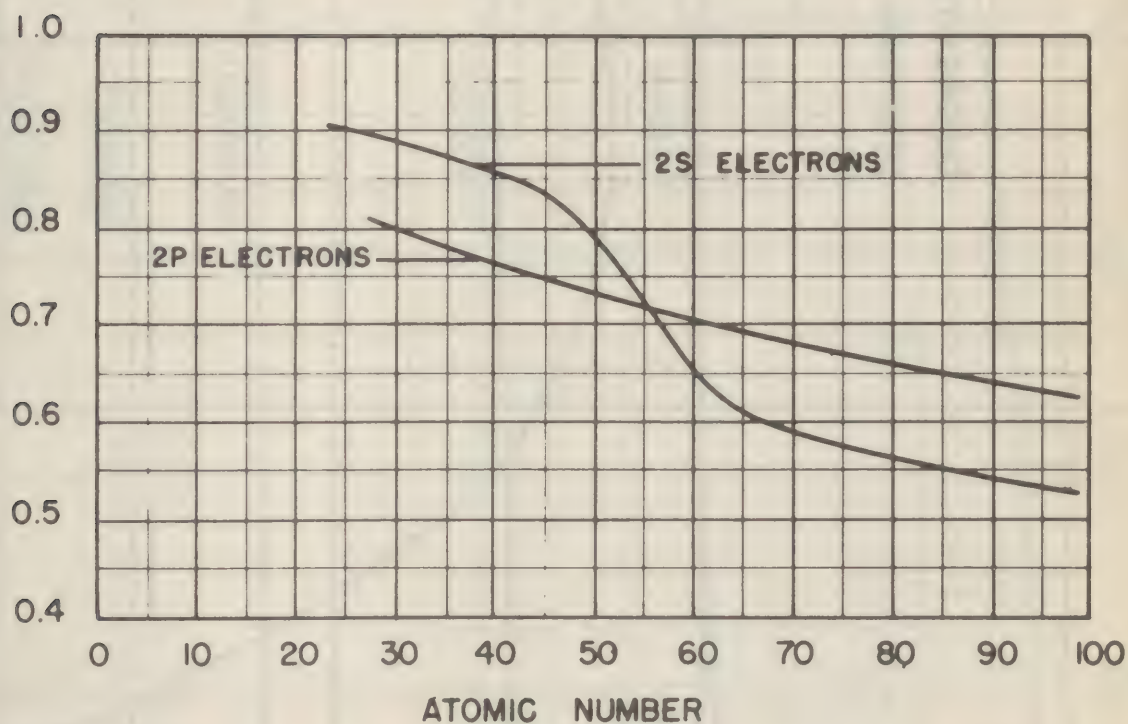
(Calculated by B.G. Hoffman, U.C. Rad. Lab.)

Fig. 12





EFFECTIVE CONTRIBUTION OF EACH K ELECTRON TO THE  
ATOMIC NUMBER



EFFECTIVE CONTRIBUTION OF EACH L ELECTRON TO THE  
ATOMIC NUMBER

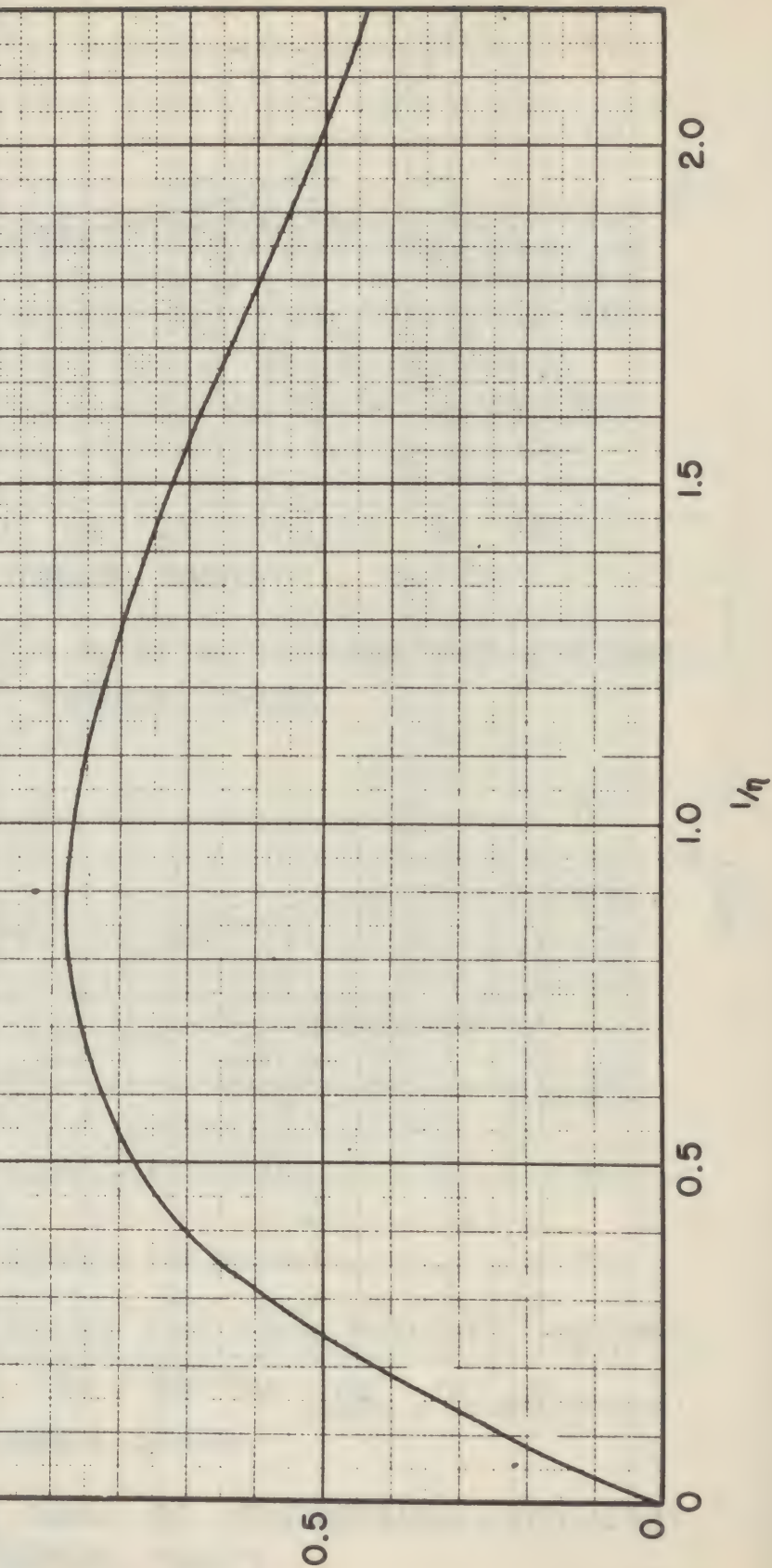
Fig. 13



# CORRECTION FOR CONTRIBUTION TO STOPPING NUMBER BY K ELECTRONS

M. S. Livingston & H. A. Bethe,  
Rev. Mod. Physics, 2, 269 (1937)

Fig. 14



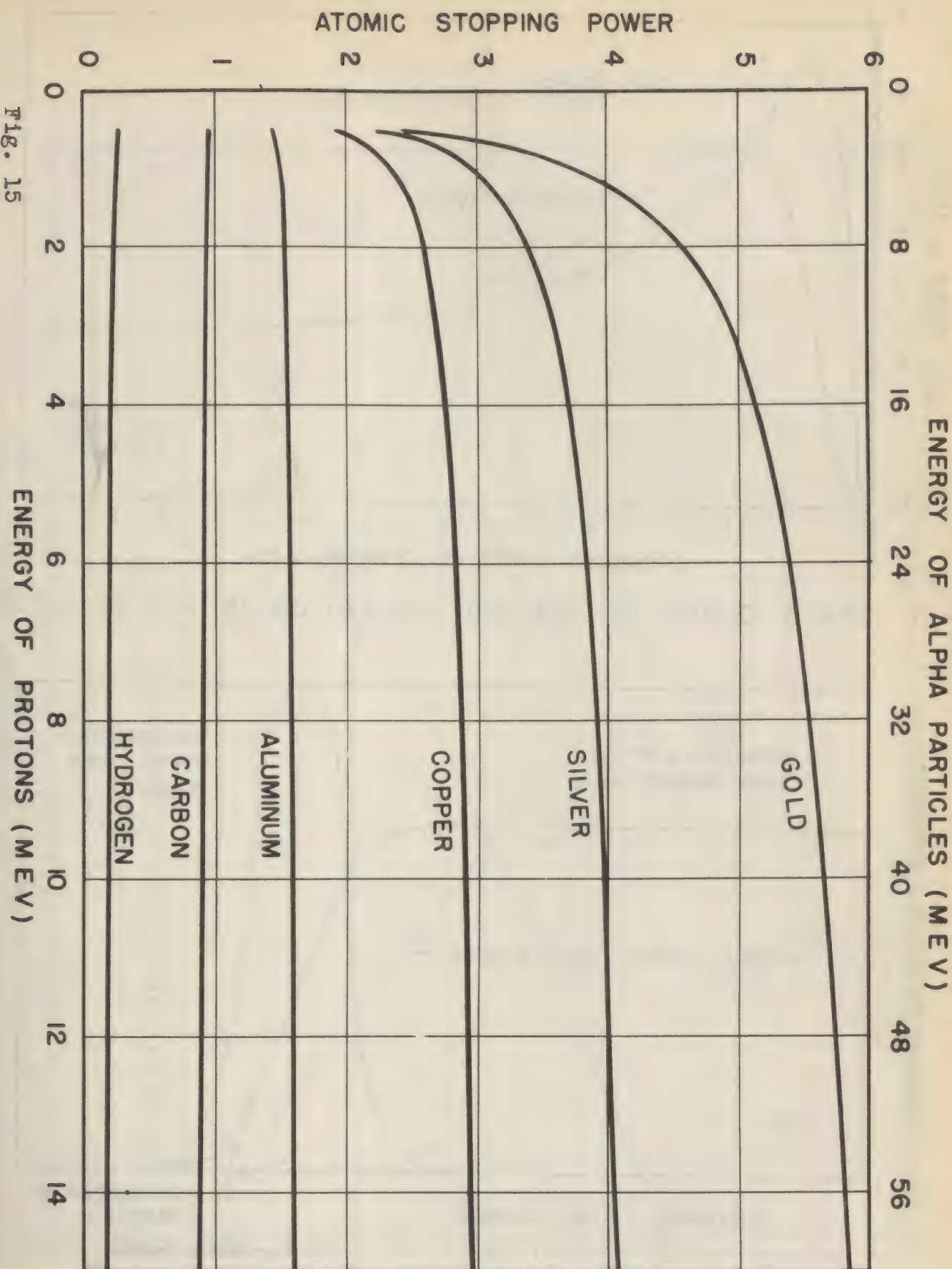
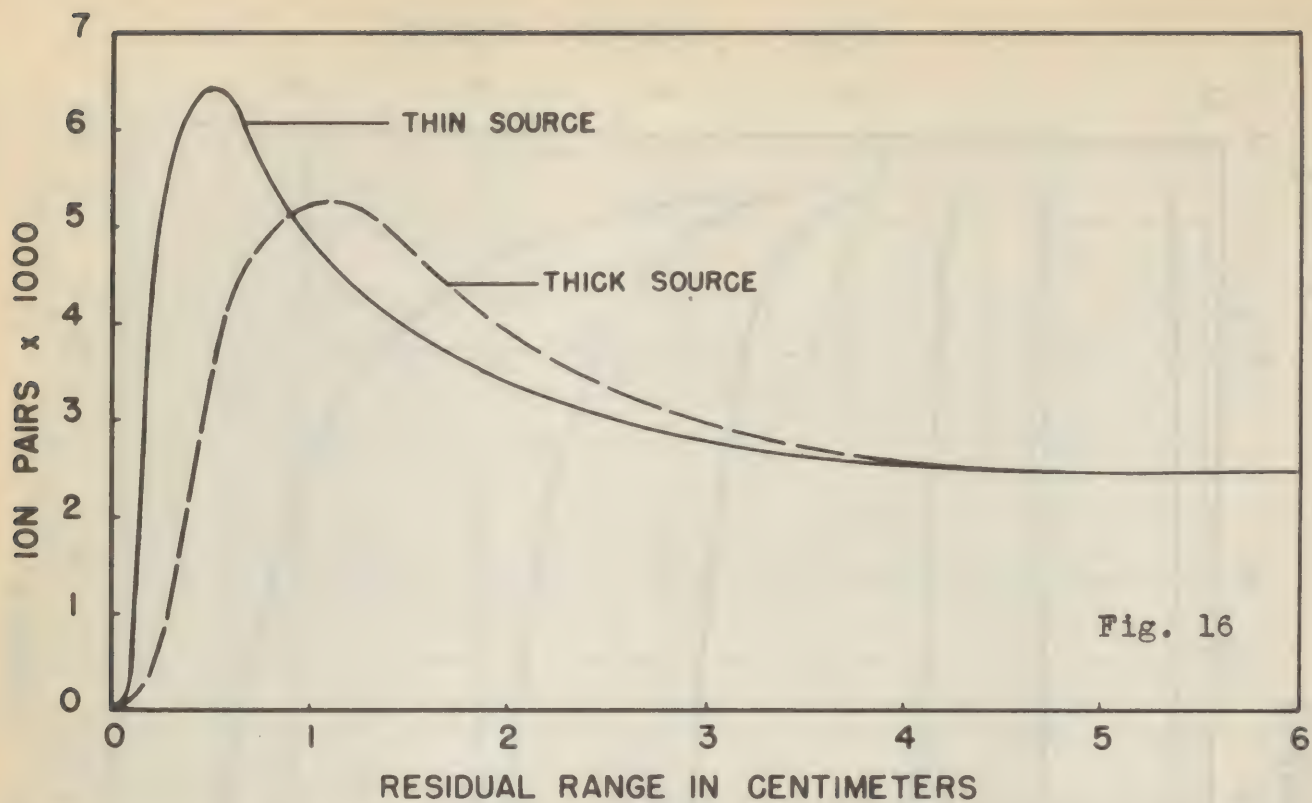
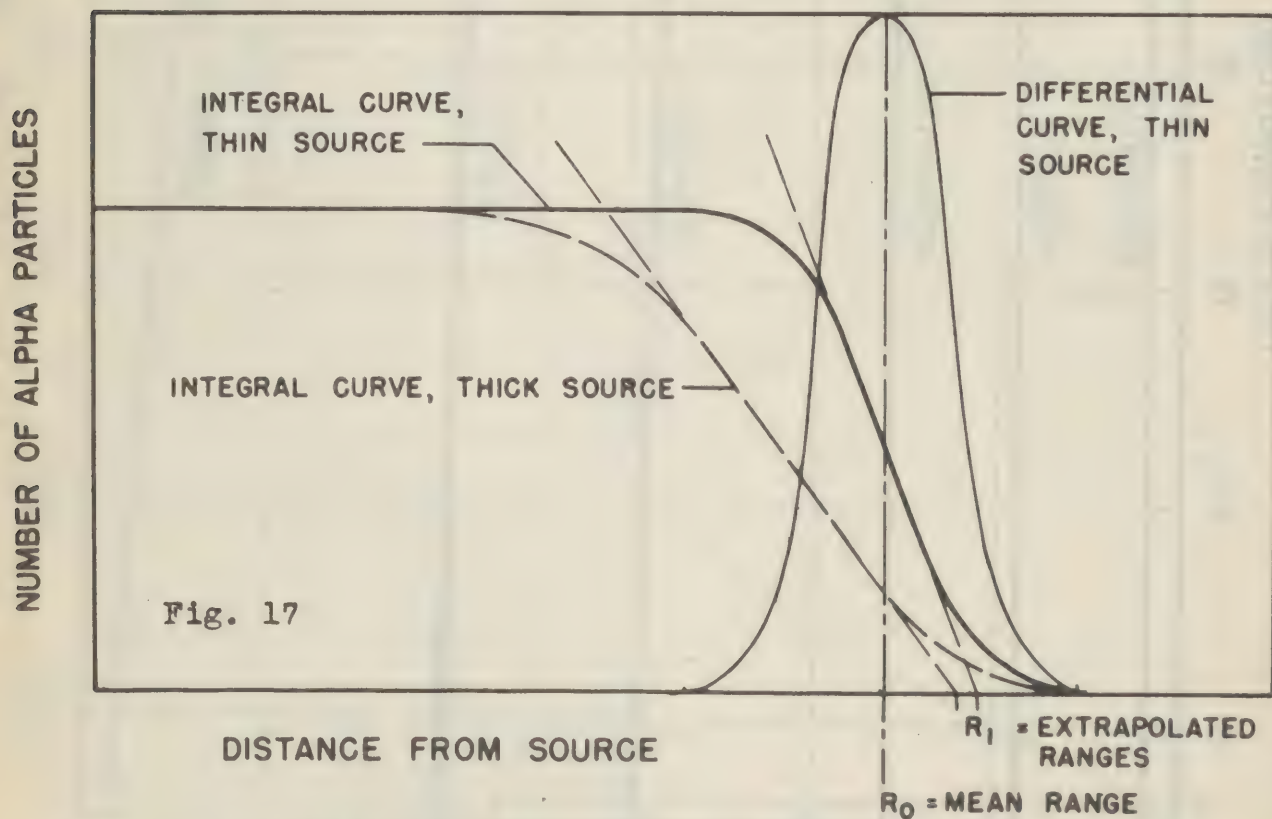


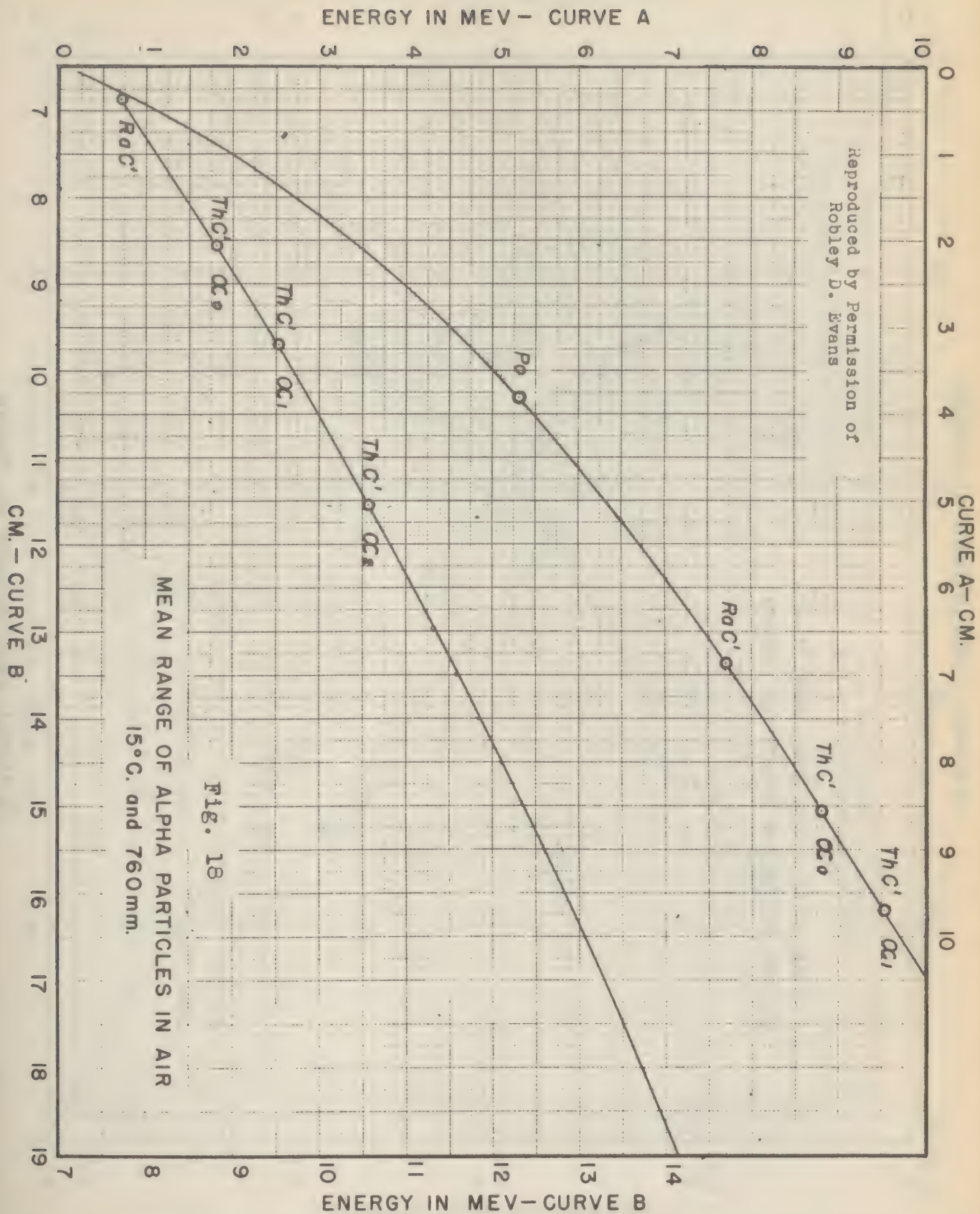
Fig. 15

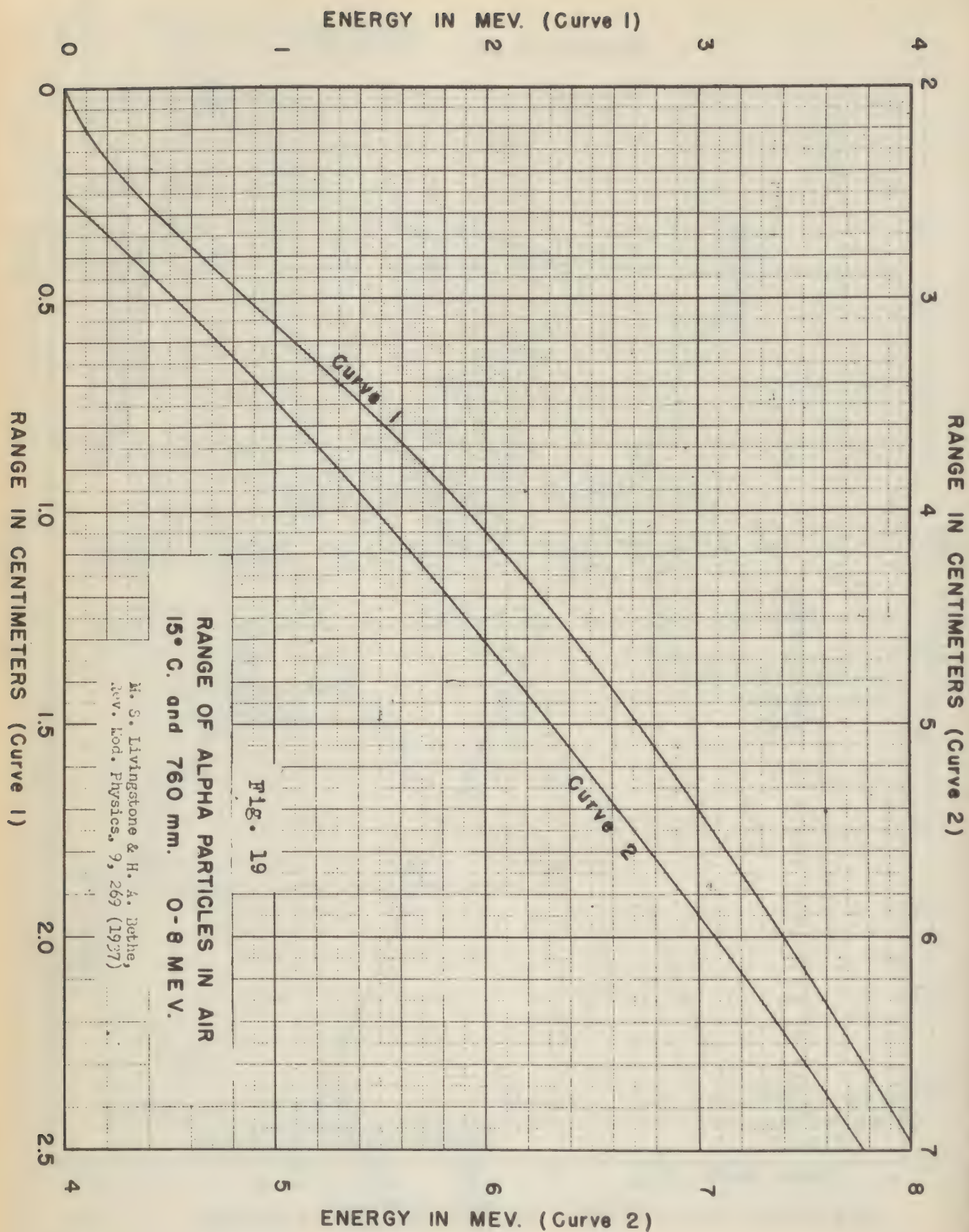


BRAGG CURVE OF SPECIFIC IONIZATION IN AIR AT N.T.P

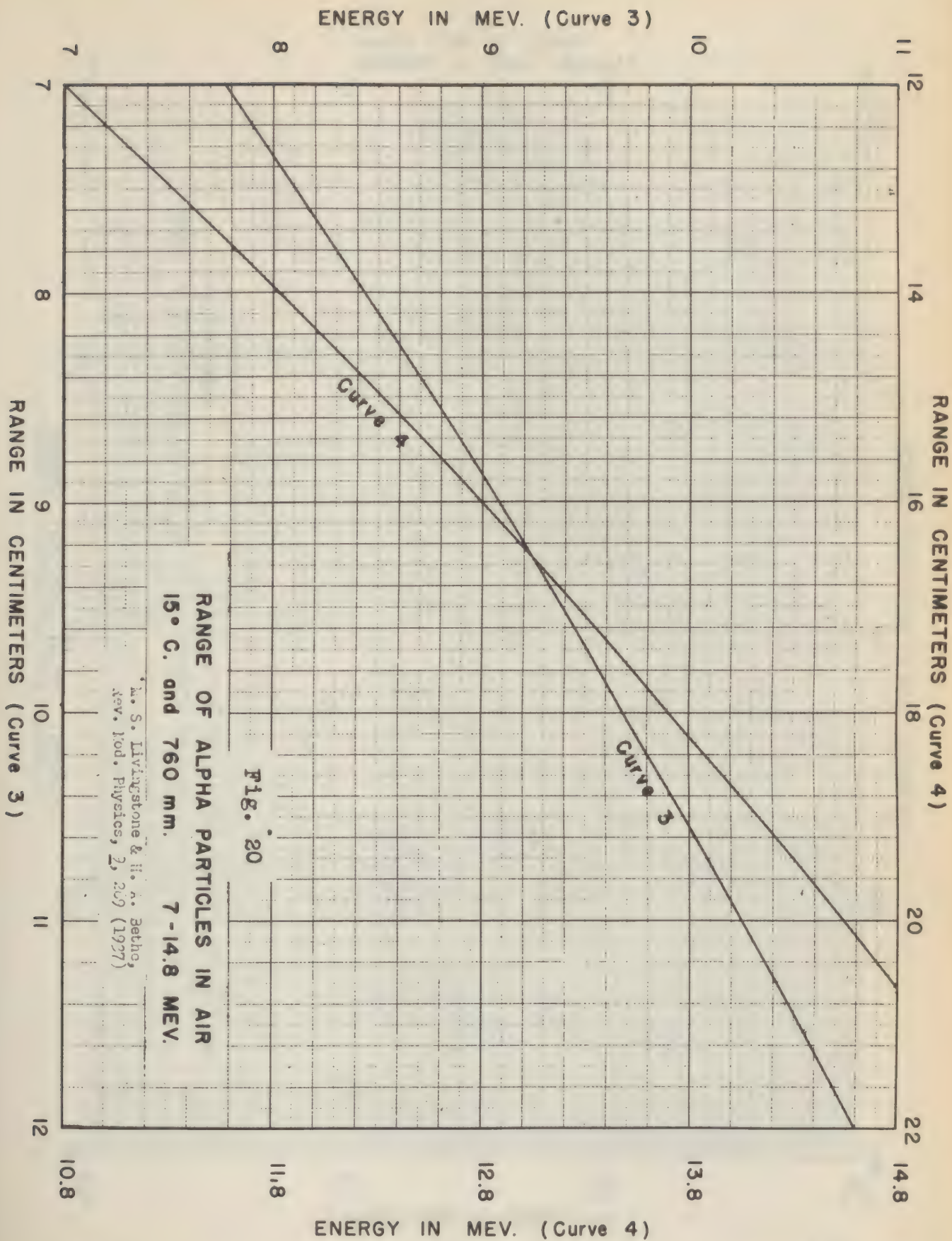




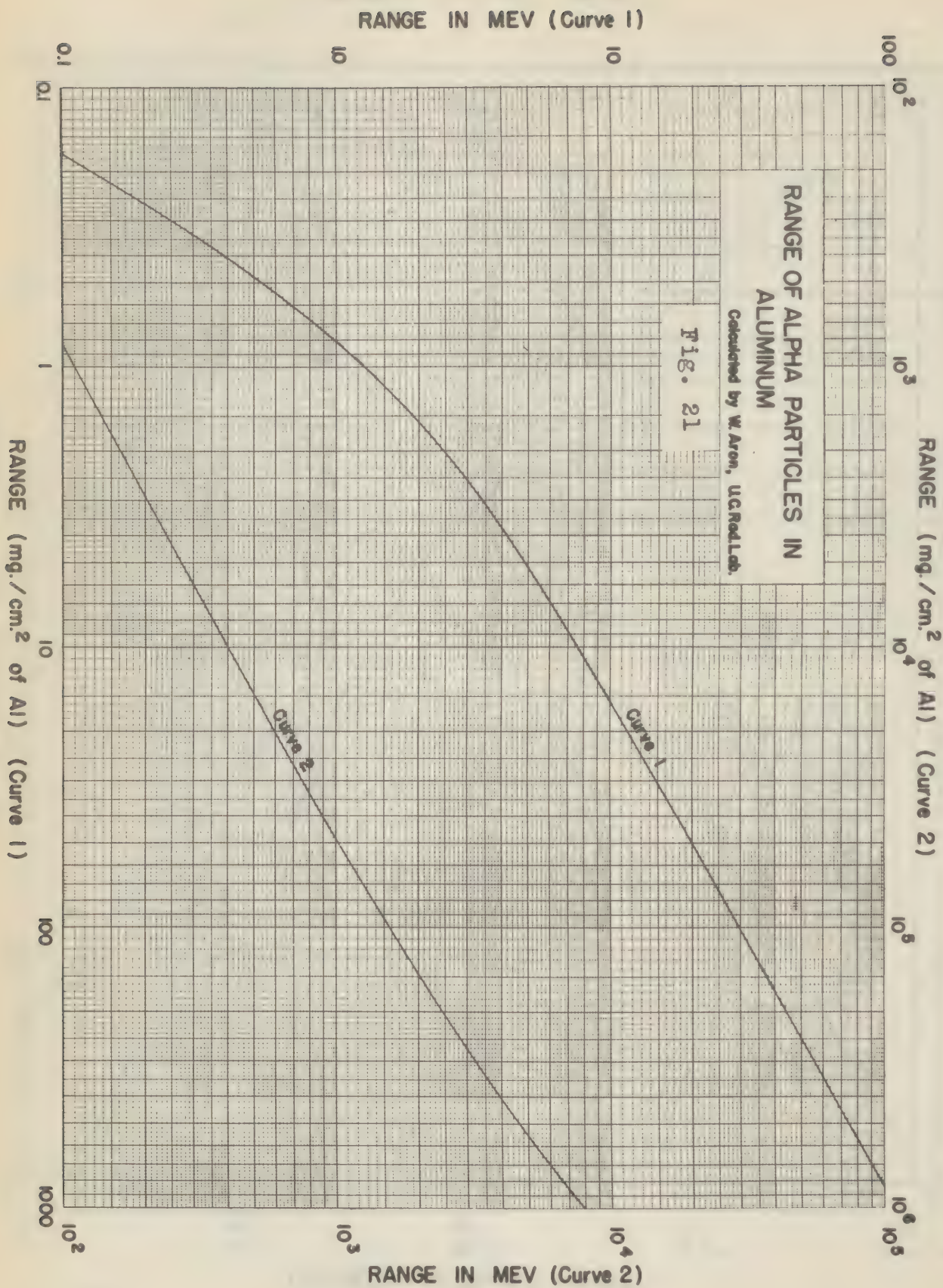


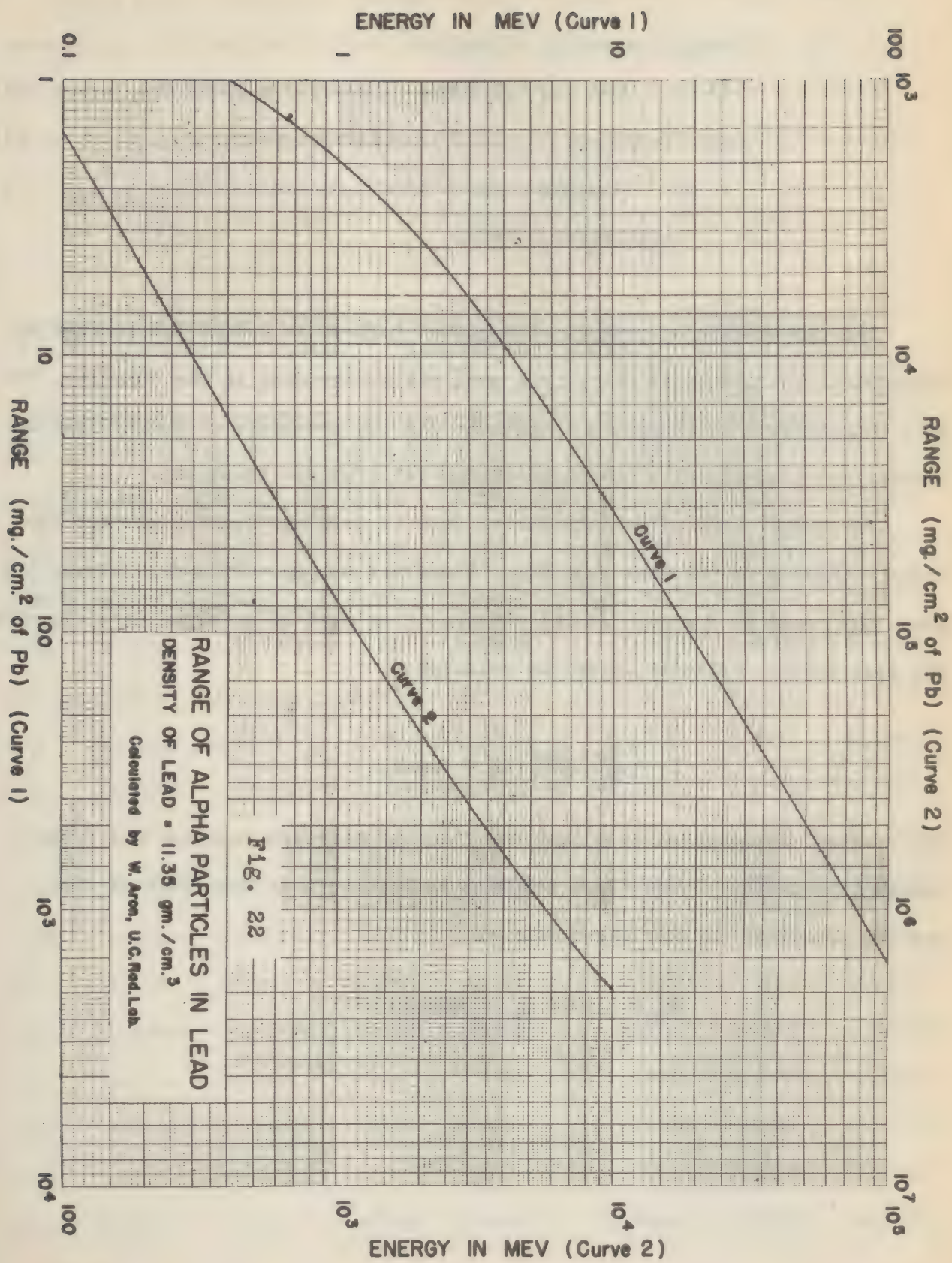














## 7. PROTON

Mass (neutral): 1.00812

charge:  $(1.60203 \pm 0.00034) \times 10^{-20}$  abs. e.m.u. (1)

magnetic moment : +2.7896 nuclear magnetons (2)

spin:  $1/2$

statistics: Fermi

The interaction of protons with matter follows in detail the section on alpha particles when unit charge and mass are substituted in the formulae. This introduces only changes in magnitude and the processes of energy loss and scattering, together with the range-energy relation are identical.

The energy loss of protons per cm path is just one quarter of that for alpha particles of the same velocity. Since the energy varies directly as the mass, the range of a proton can be obtained from that of an alpha particle with the same initial velocity, from the relation

$$R = \frac{M_p}{M_\alpha} \frac{Z_\alpha^2}{Z_p^2} R_\alpha + \text{Const.}$$

The constant is included to adjust the range at very low energies where the charge fluctuation of the alpha particle is less certain than that of the proton. Blackett (2) has given this as

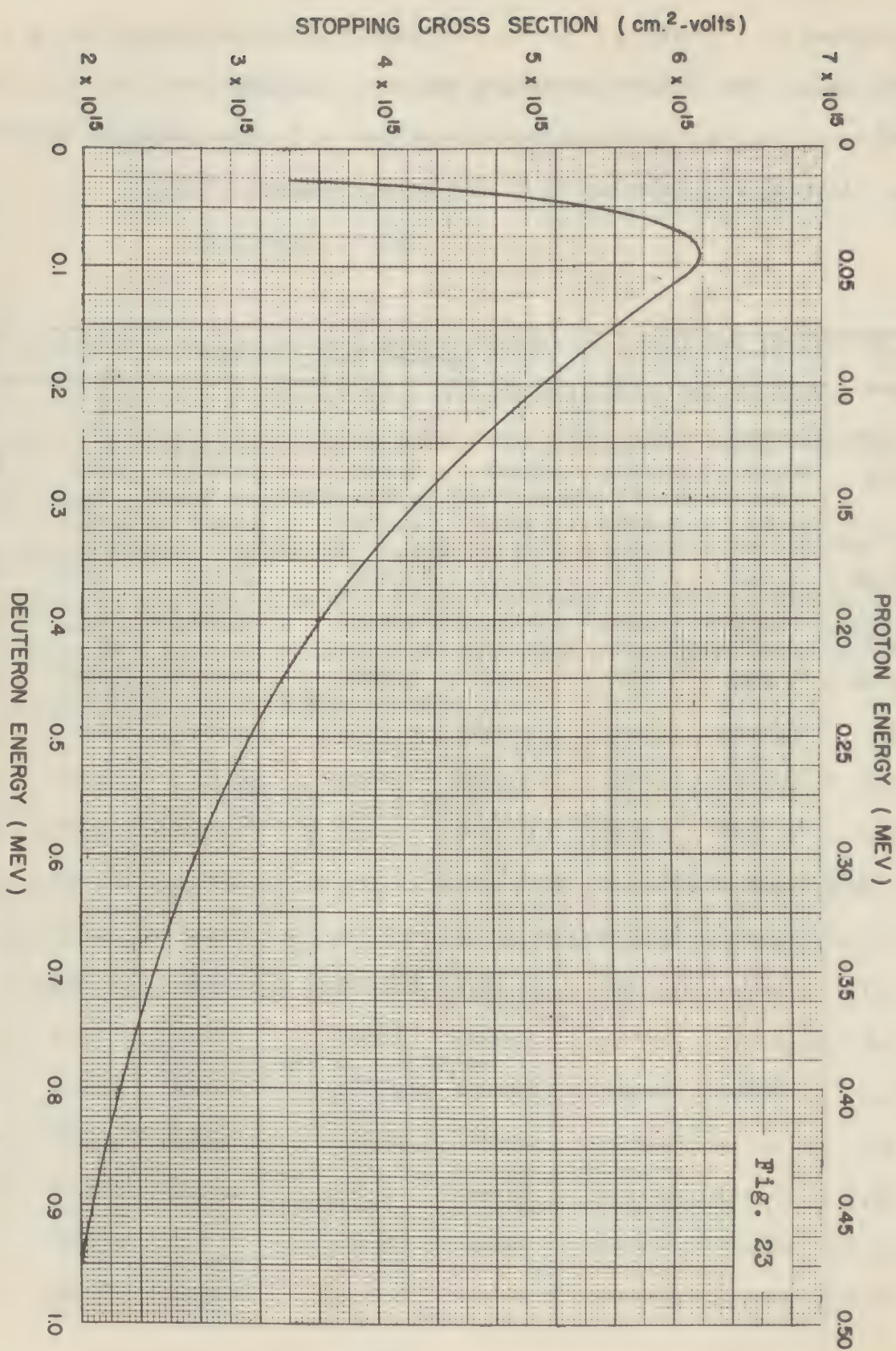
$$R_p = 1.0072 R_\alpha - 0.20 \text{ cm}$$



Table 8. Secondary Electron Produced by Proton in Tissue

Table gives the number of electrons, with an energy greater than E, produced by a proton per micron path length in tissue of density,  $\rho = 1$ . The values for similar substances but with different densities are obtained by multiplying by the density in gm per cc.<sup>2</sup> Data reprinted from Lea, D. E., *Actions of Radiations on Living Cells*, Cambridge (1947).

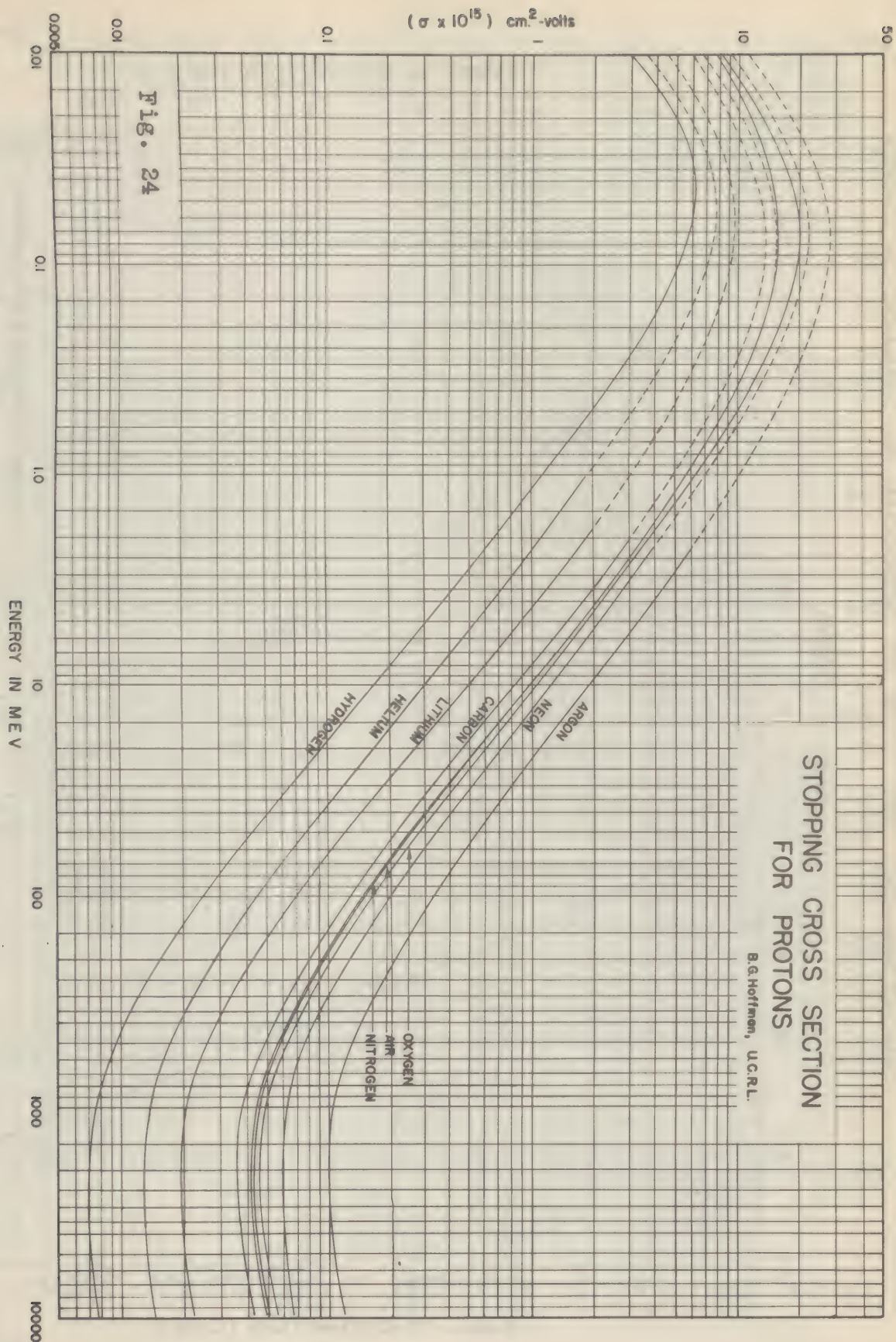
E mev	proton energy in mev						
	1	2	3	4	6	8	10
0.1	30.58	15.66	10.52	7.921	5.301	3.984	3.191
0.25	11.35	6.042	4.110	3.113	2.096	1.580	1.267
0.45	5.650	3.193	2.211	1.689	1.146	0.8673	0.6976
0.65	3.458	2.097	1.480	1.141	0.7810	0.5934	0.4784
0.85	2.298	1.517	1.093	0.8507	0.5876	0.4483	0.3624
1.1	1.441	1.089	0.8076	0.6364	0.4447	0.3412	0.2767
1.5	0.6636	0.7001	0.5486	0.4421	0.3152	0.2441	0.1990
1.9	0.2137	0.4752	0.3986	0.3297	0.2402	0.1879	0.1540
2.25	-----	0.3440	0.3112	0.2641	0.1965	0.1551	0.1277
2.75	-----	0.2145	0.2248	0.1993	0.1533	0.1227	0.1018
3.75	-----	0.0591	0.1212	0.1216	0.1015	0.0838	0.0707
5.5	-----	-----	0.0306	0.0536	0.0562	0.0498	0.04355
6.5	-----	-----	0.0007	0.0312	0.0413	0.0386	0.03458
8.5	-----	-----	-----	0.0022	0.0219	0.0241	0.02298
10.5	-----	-----	-----	-----	0.0100	0.0151	0.01580
12.5	-----	-----	-----	-----	0.0018	0.0090	0.01091
15.5	-----	-----	-----	-----	-----	0.0028	0.00595



# STOPPING CROSS SECTION FOR PROTONS AND DEUTERONS IN HYDROGEN

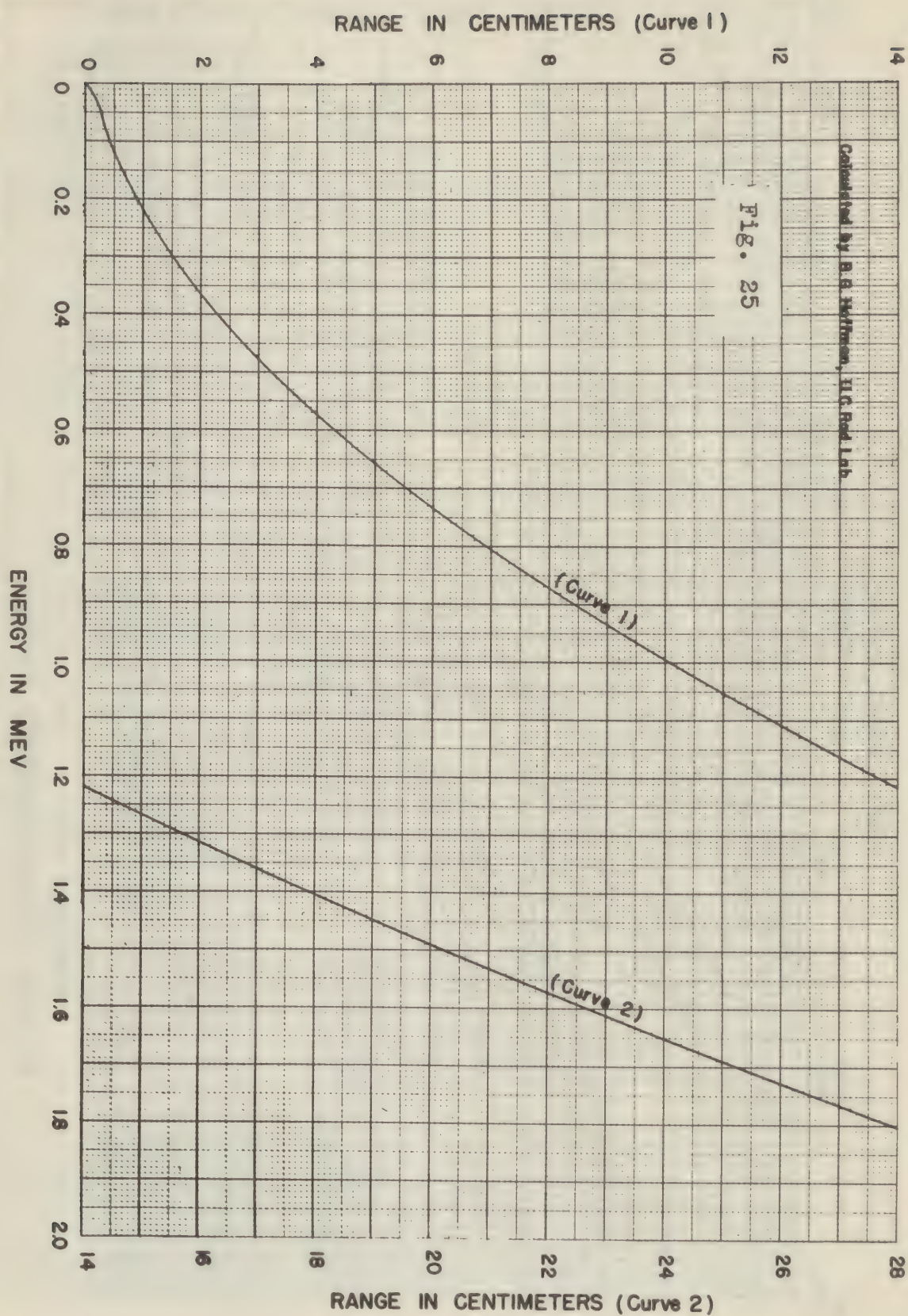
(Ashkin, L.A. Report 12-R, Revised U.C. Rad. Lab.)



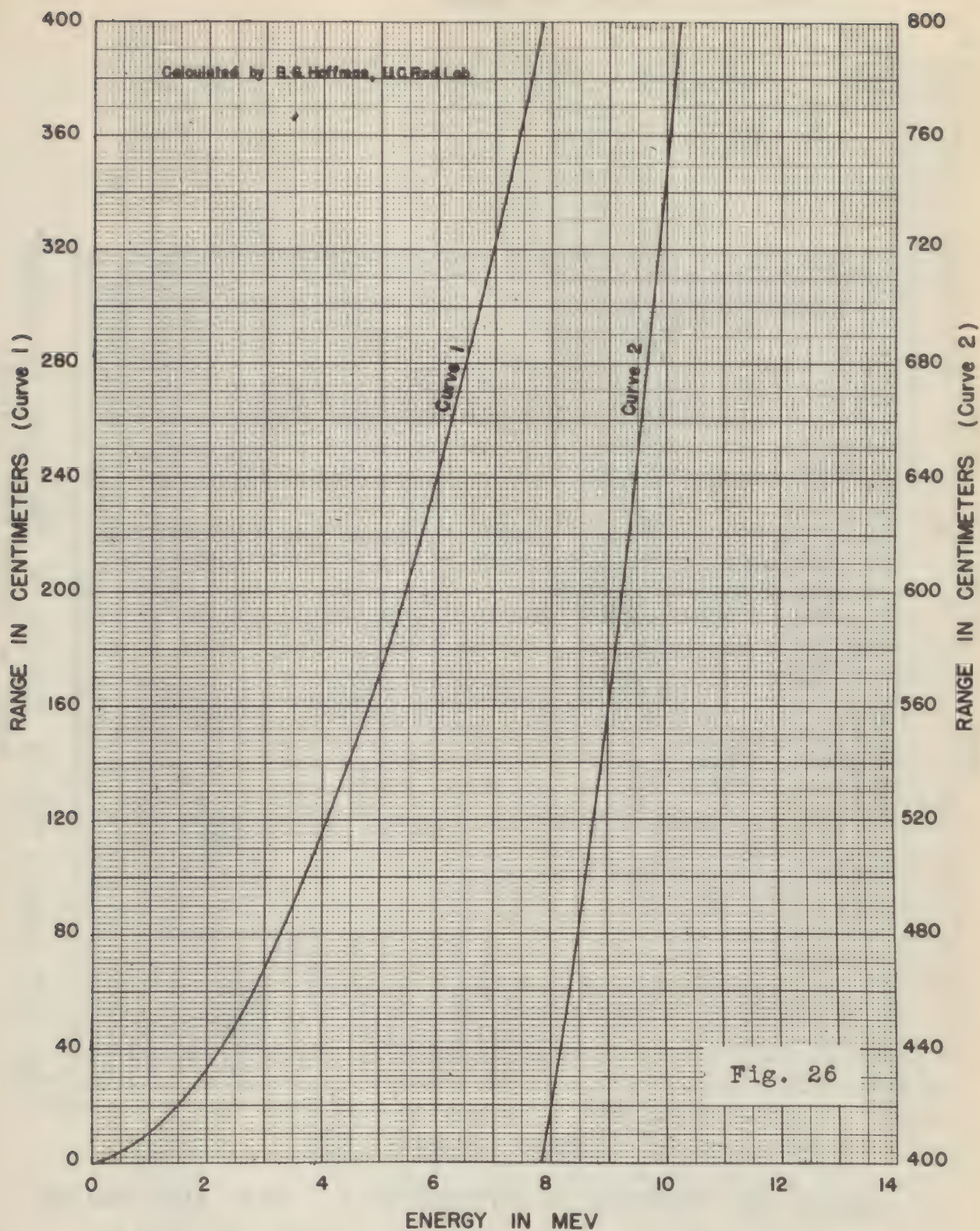




# RANGE OF PROTONS IN HYDROGEN AT 15° C. AND 760 mm. OF Hg.

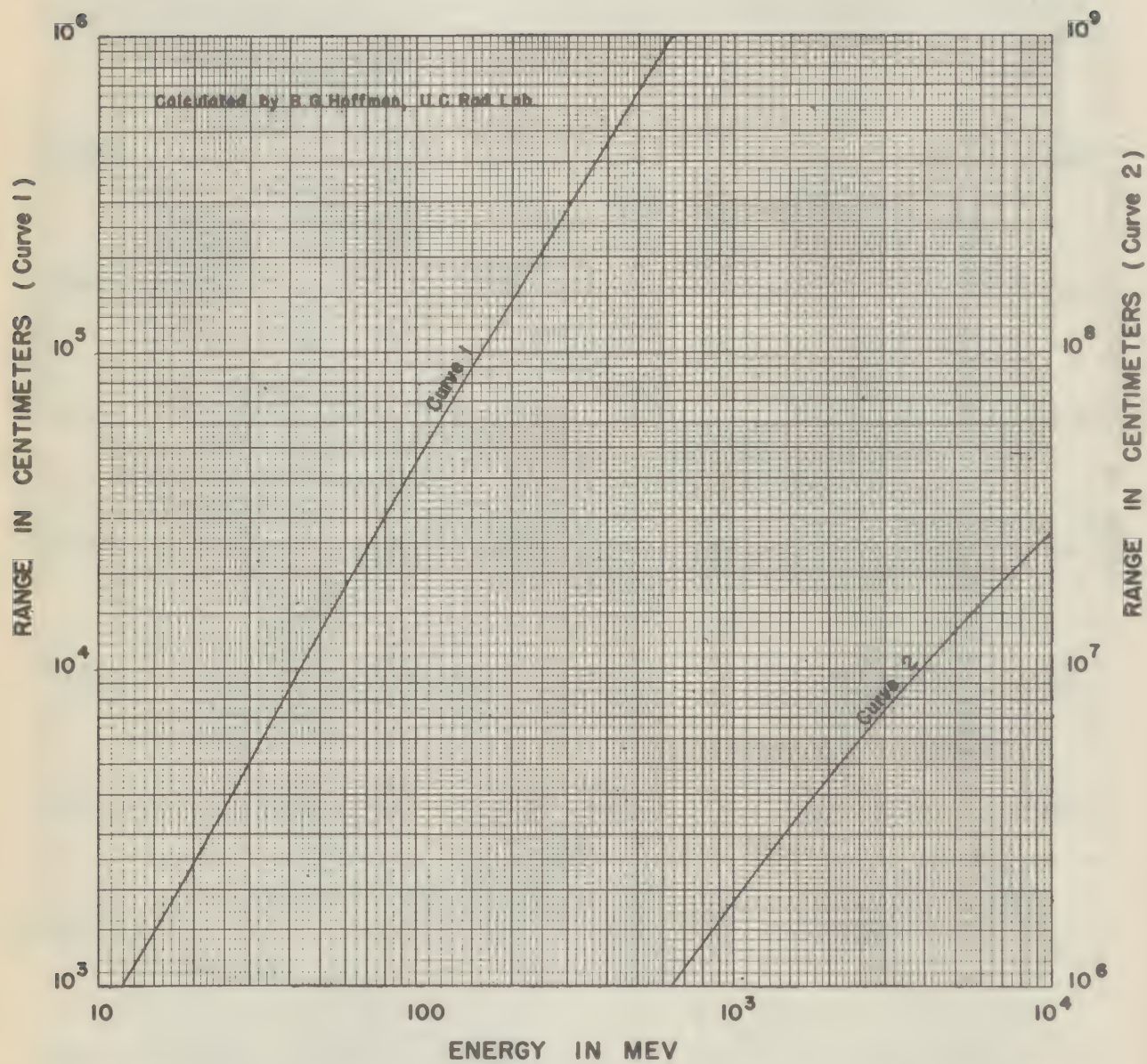






RANGE OF PROTONS IN HYDROGEN AT 15° C. AND 760 mm.



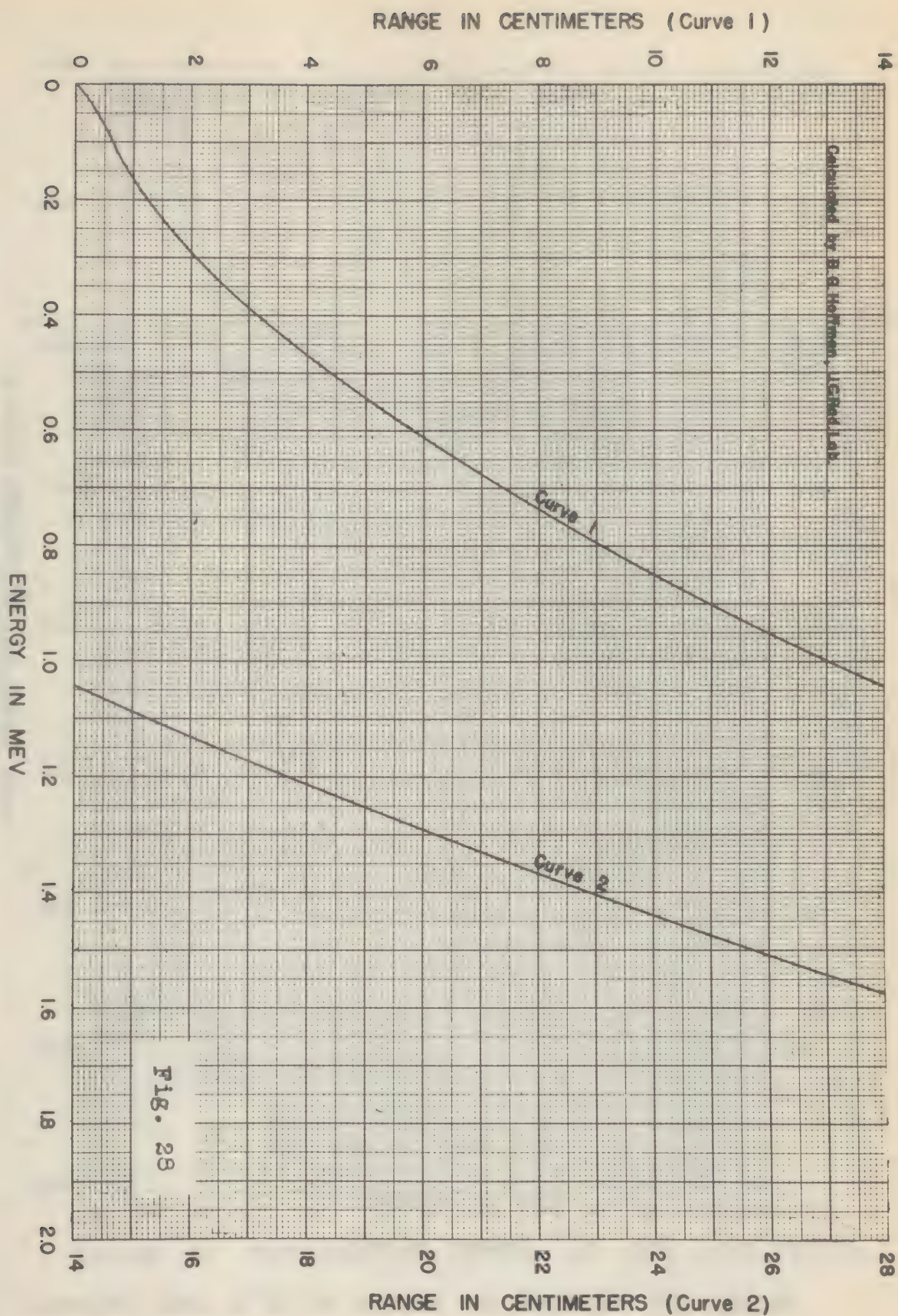


RANGE OF PROTONS IN HYDROGEN AT 15° C. AND 760 mm.

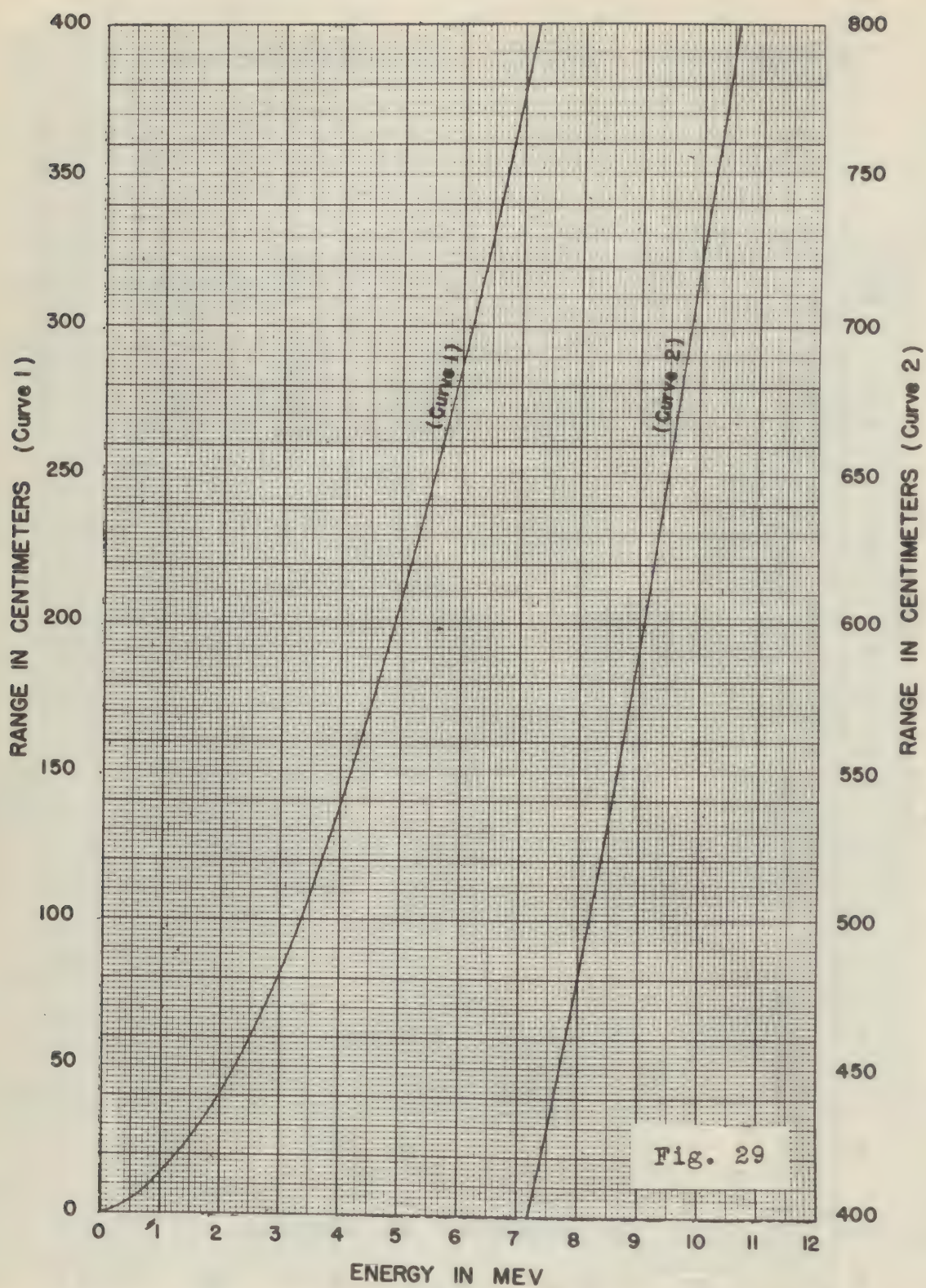
Fig. 27



# RANGE OF PROTONS IN HELIUM AT 15° C. AND 760 mm.

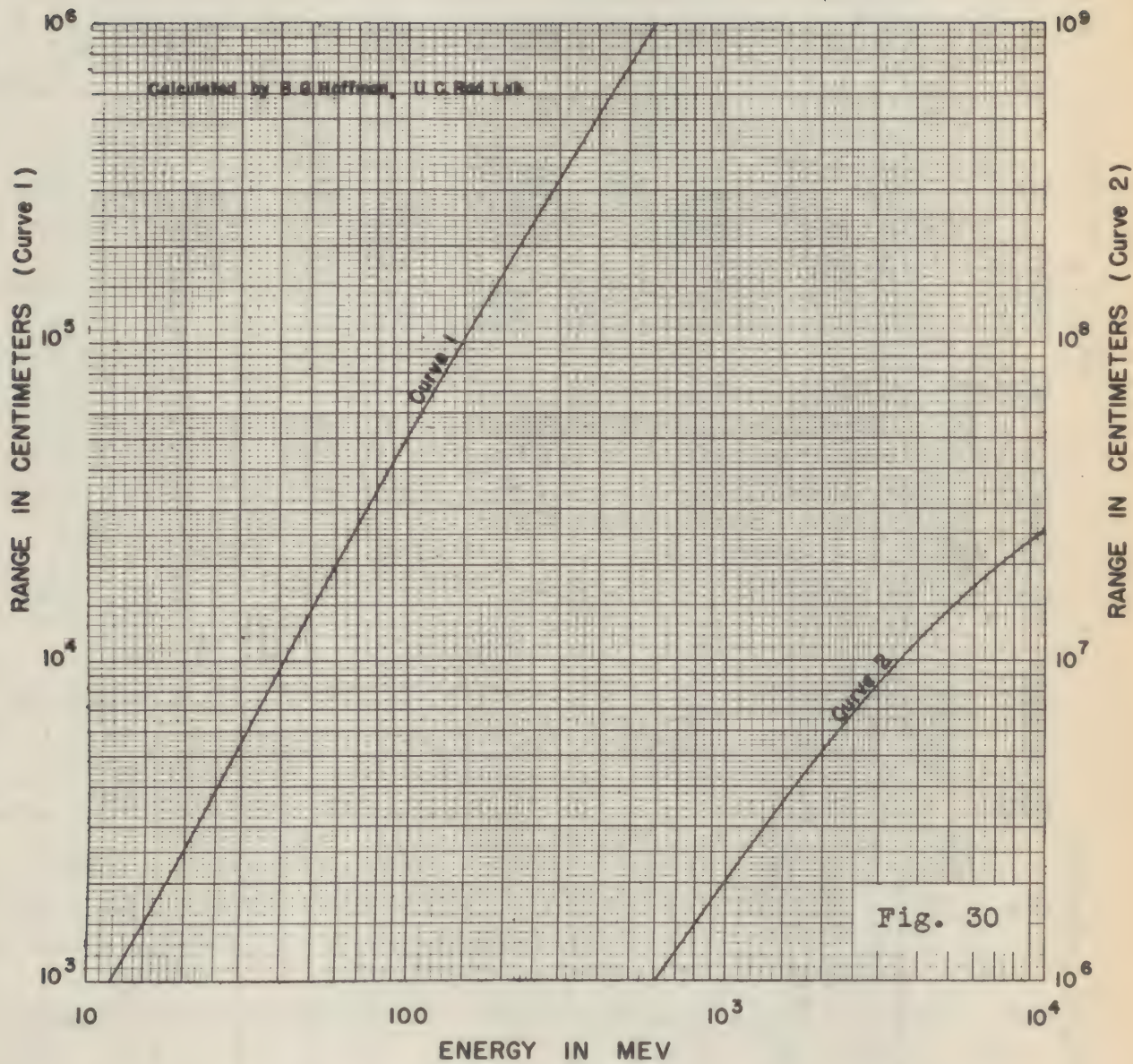






RANGE OF PROTONS IN HELIUM AT 15° C. AND 760 mm.





RANGE OF PROTONS IN HELIUM AT 15° C. AND 760 mm.

# RANGE OF PROTONS IN LITHIUM

(B. G. Hoffman, U.C. Rad. Lab.)

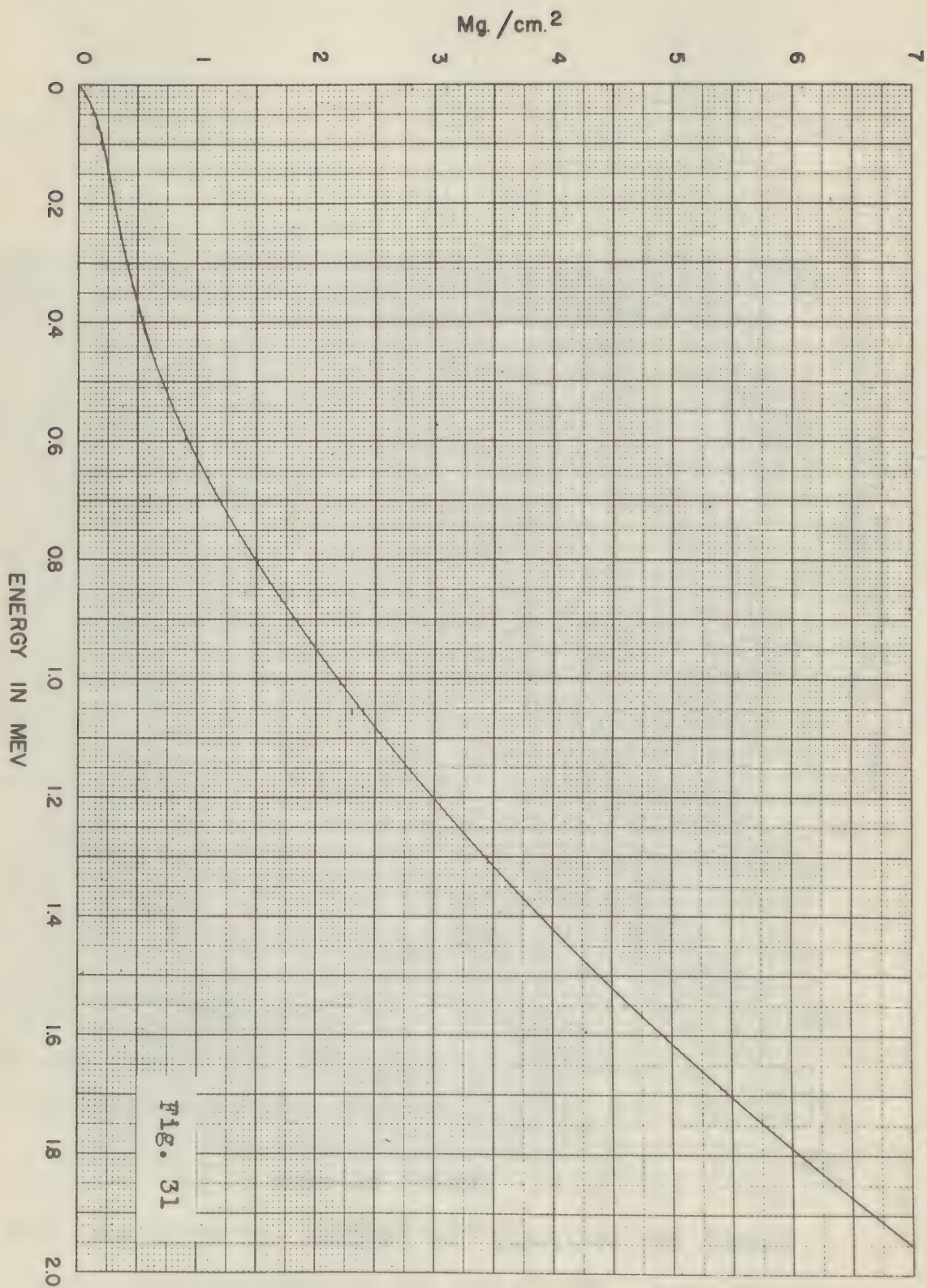
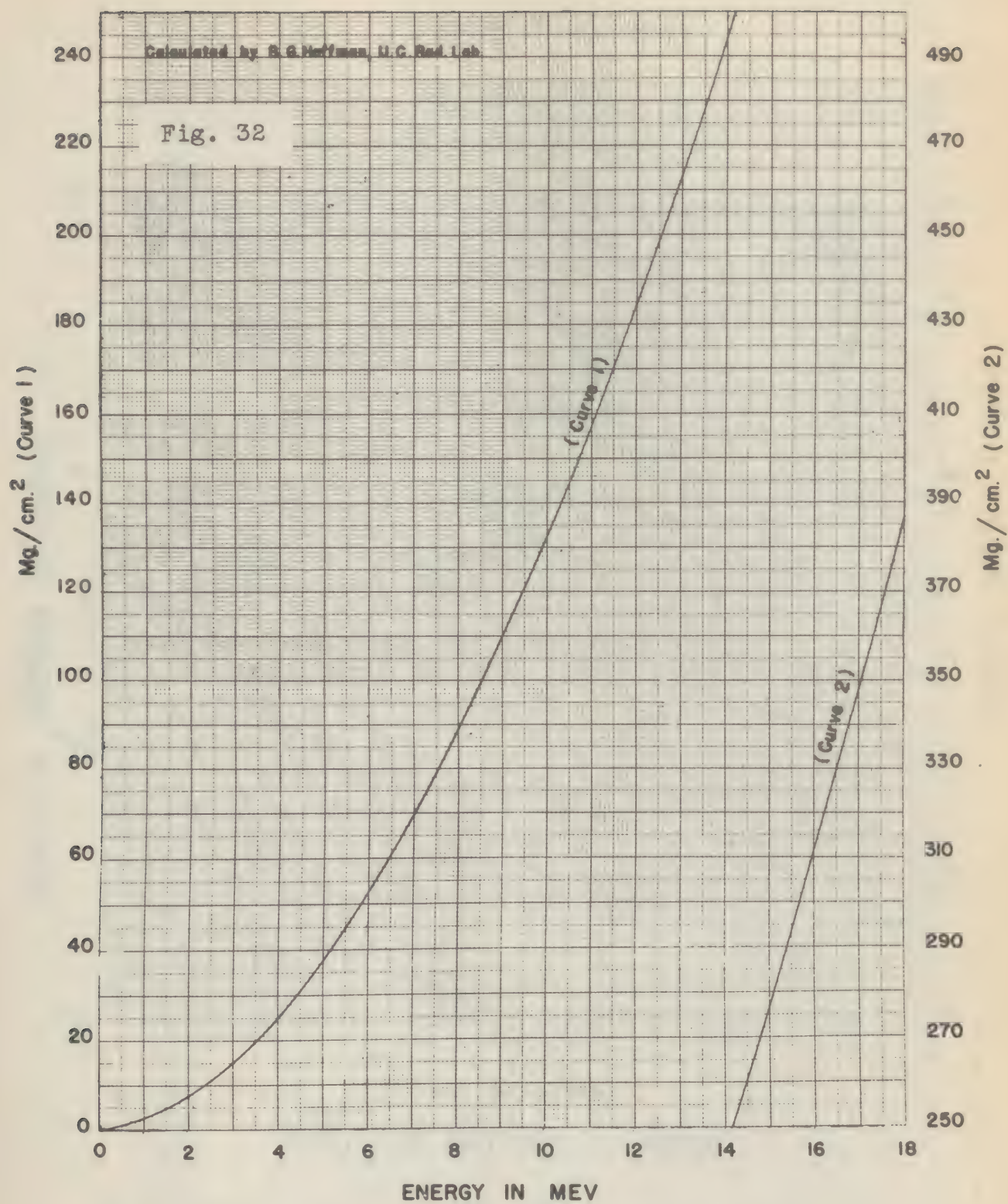
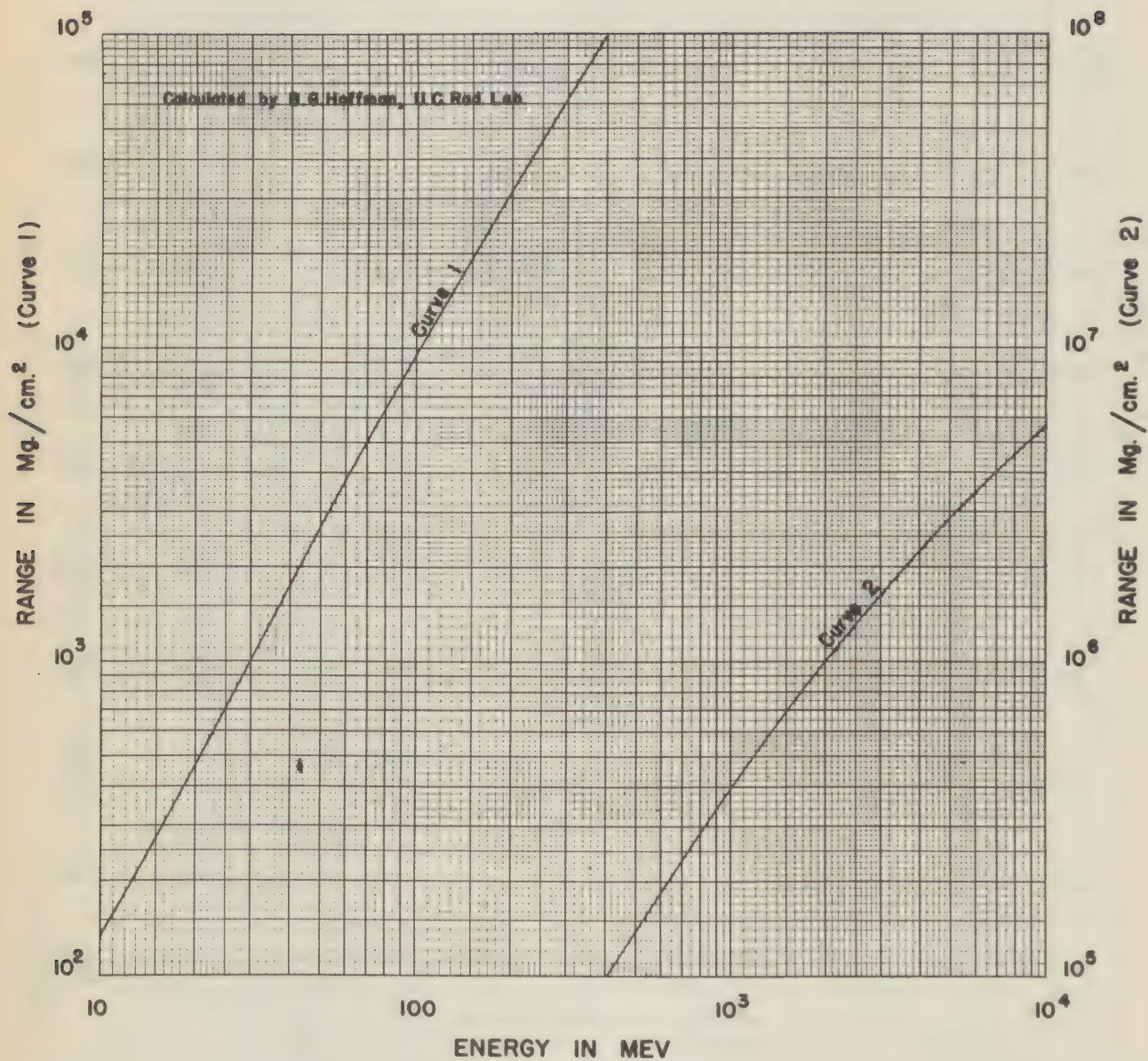


Fig. 31





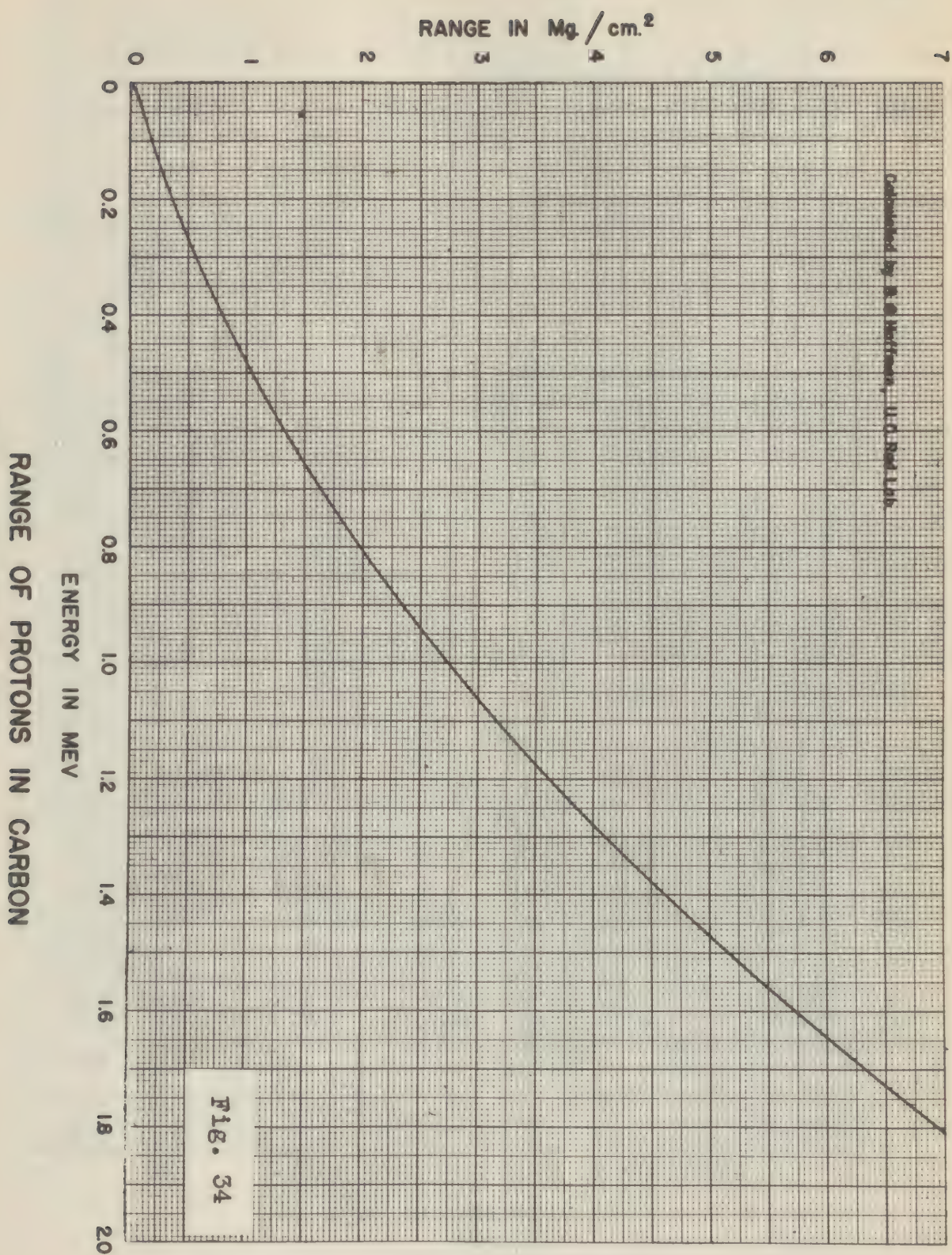
RANGE OF PROTONS IN LITHIUM



RANGE OF PROTONS IN LITHIUM

Fig. 33







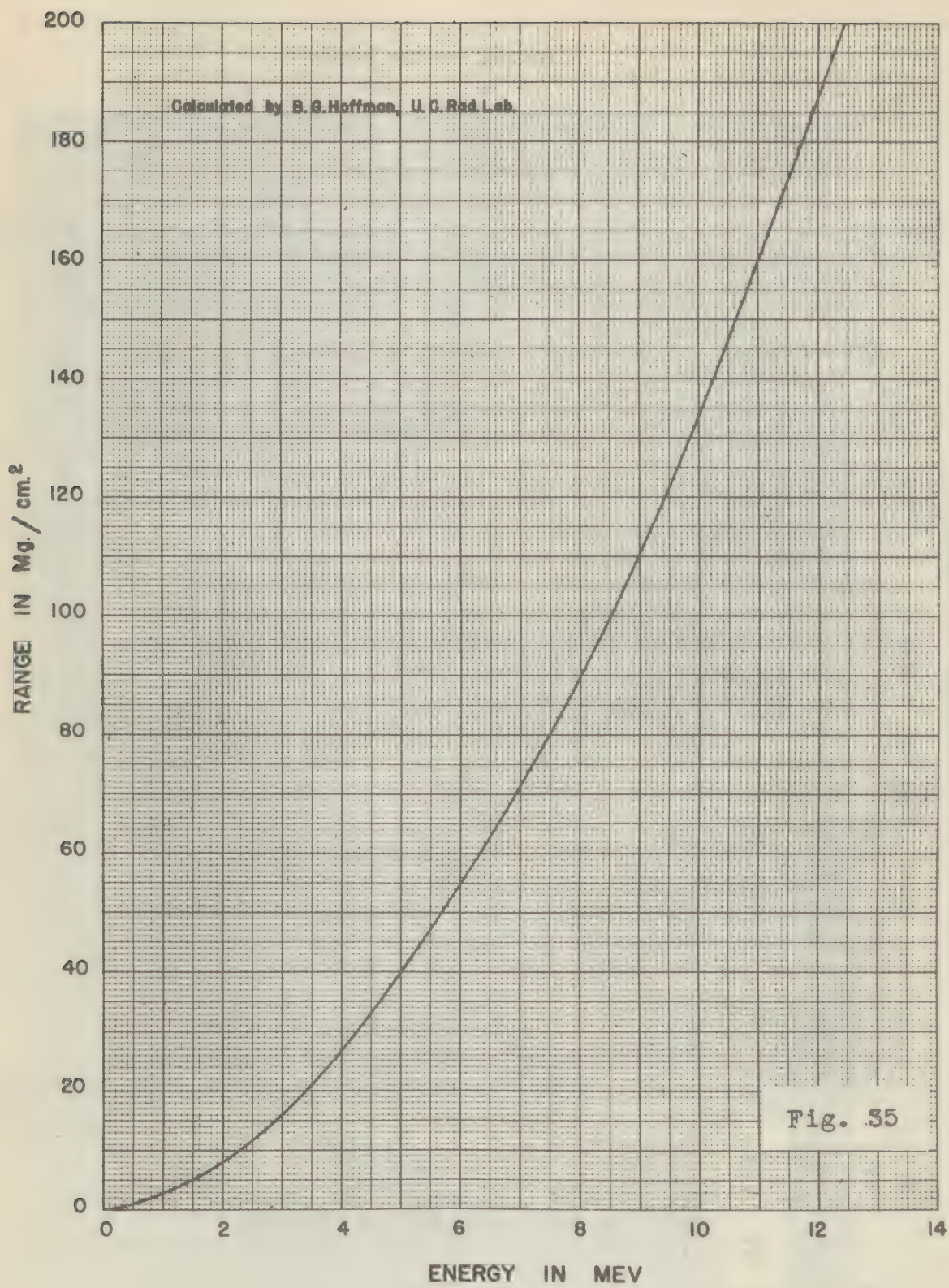


Fig. 35

RANGE OF PROTONS IN CARBON



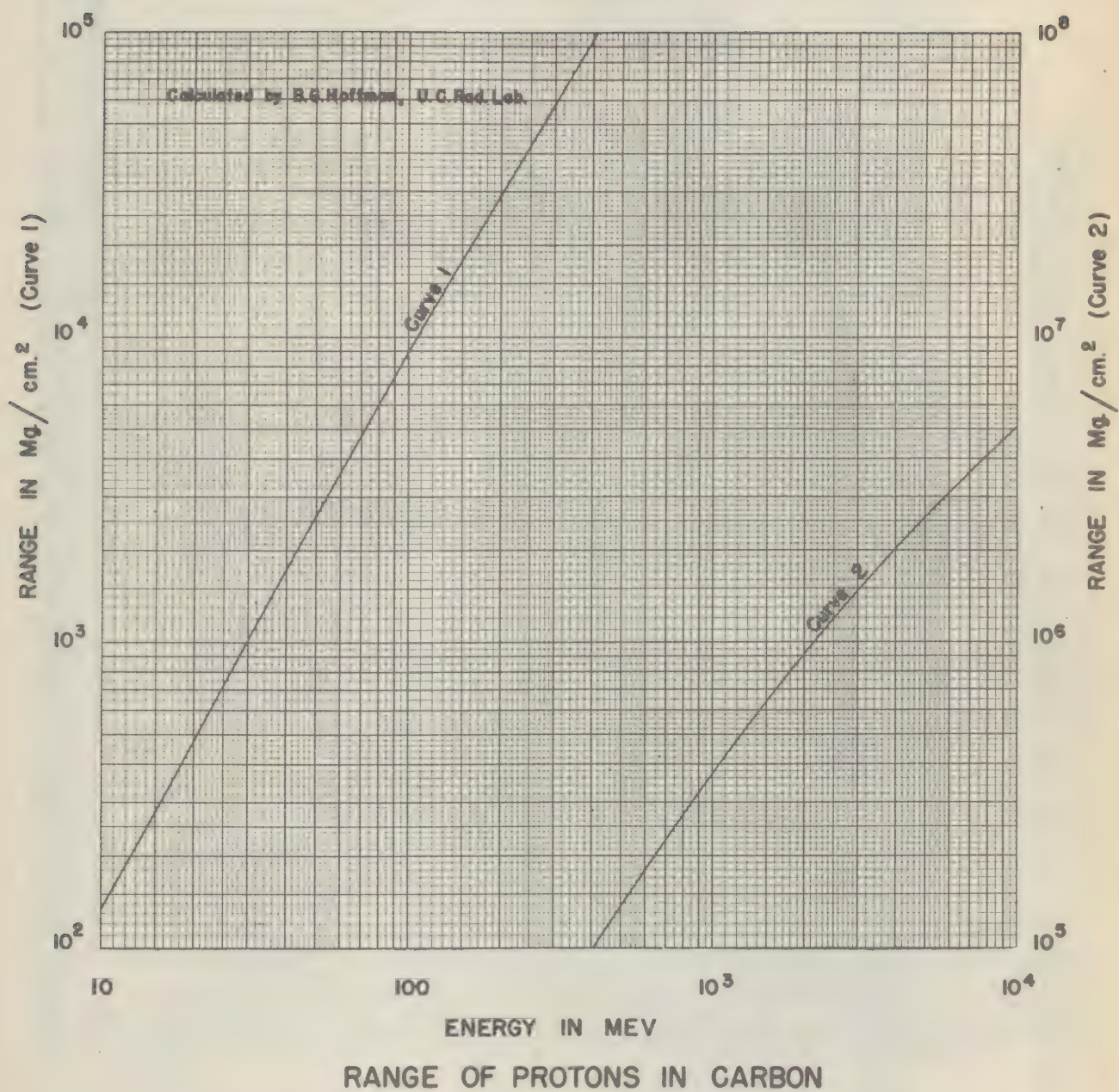
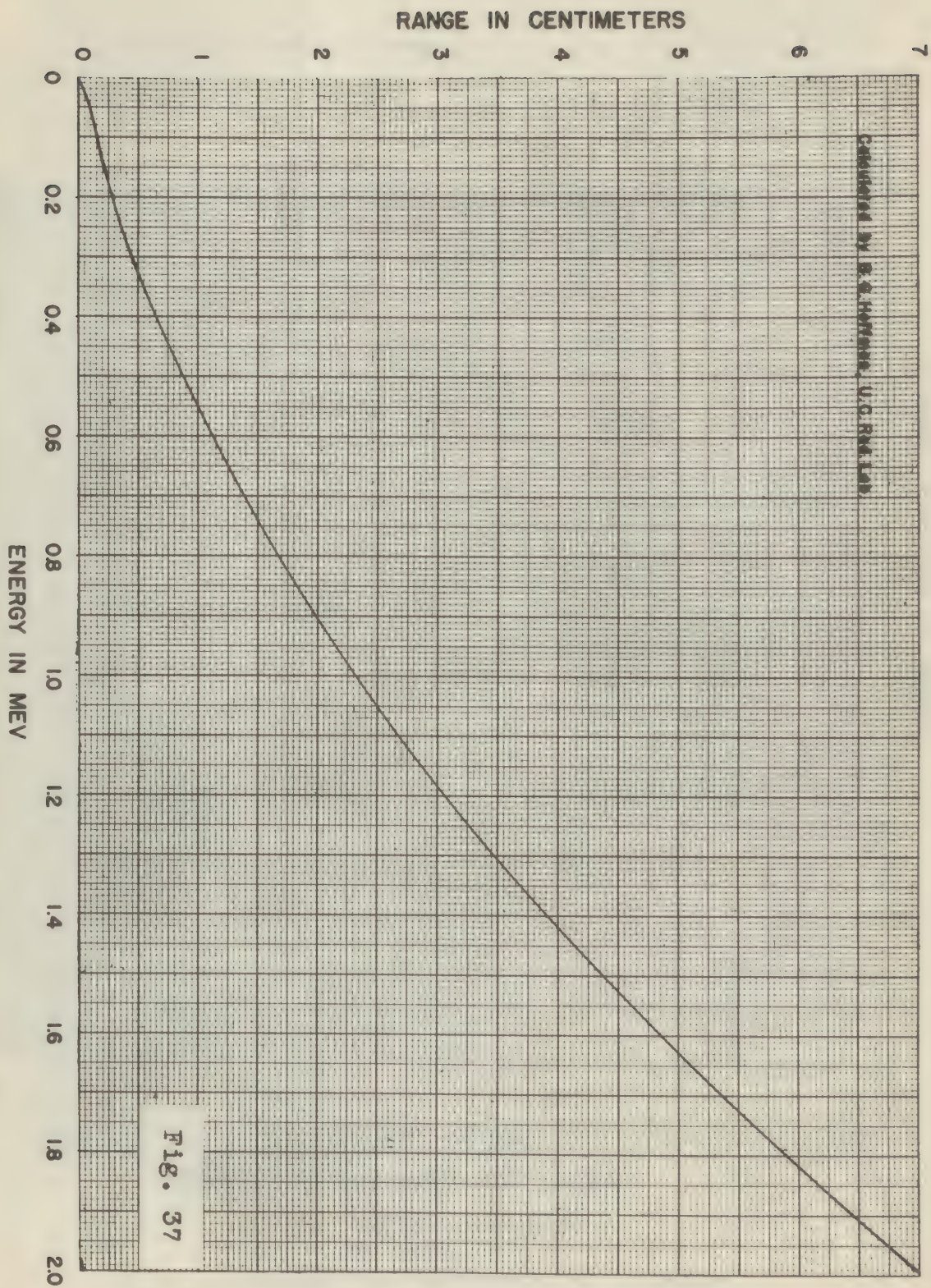


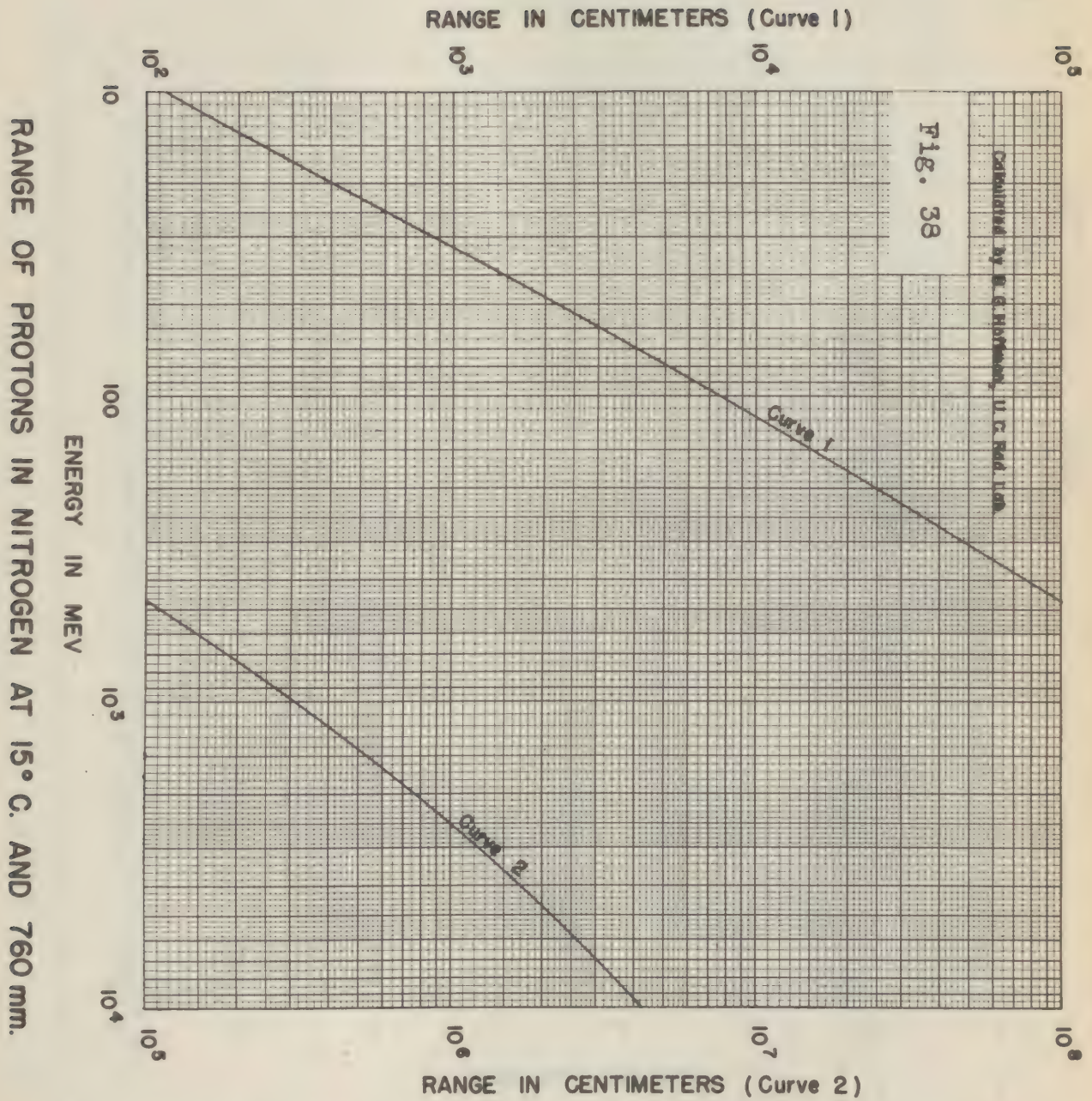
Fig. 36



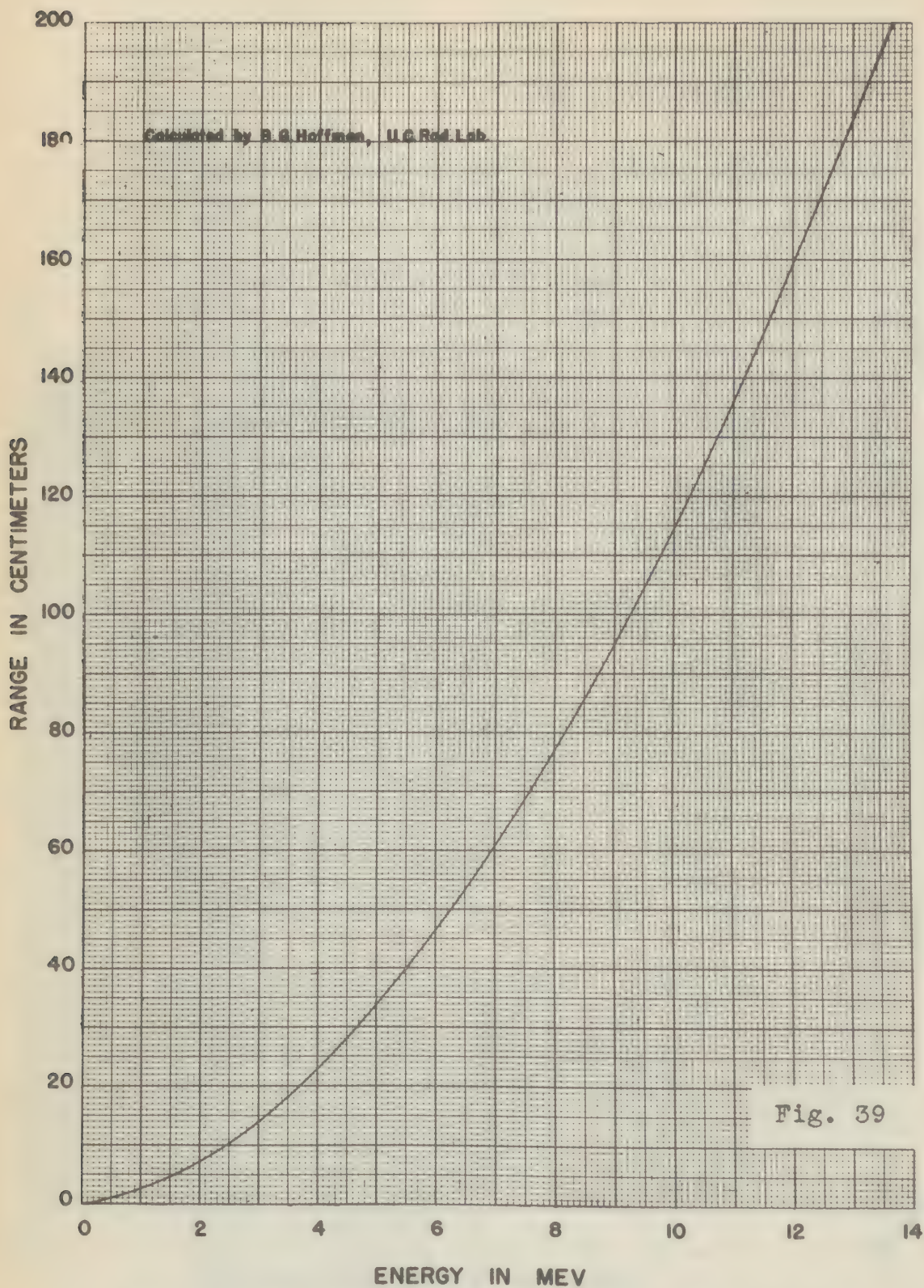
# RANGE OF PROTONS IN NITROGEN AT 15° C. AND 760 mm.











RANGE OF PROTONS IN NITROGEN AT 15°C. AND 760 mm.



ENERGY IN MEV

0.5

1.0

1.5

2.0

0

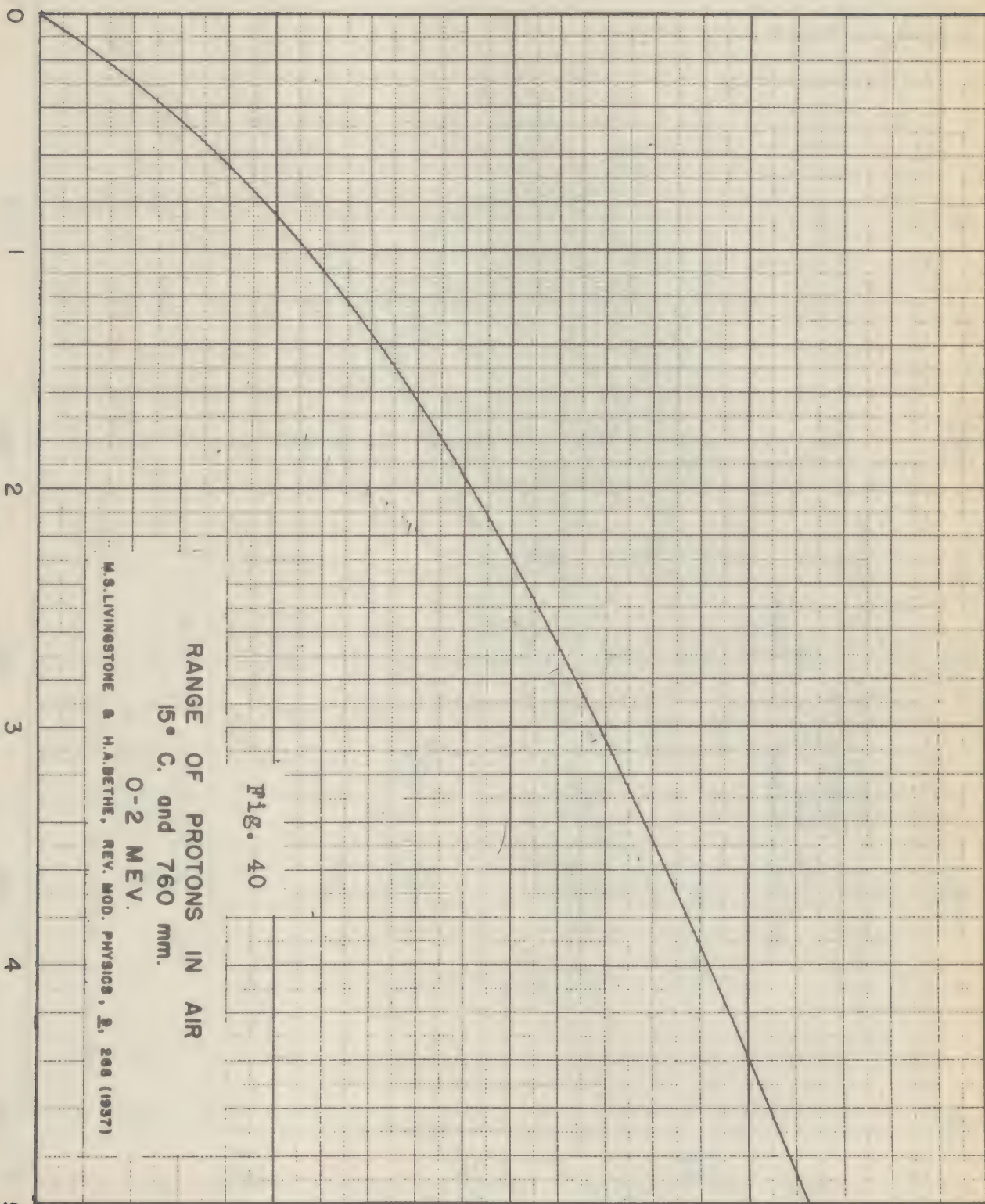


Fig. 40

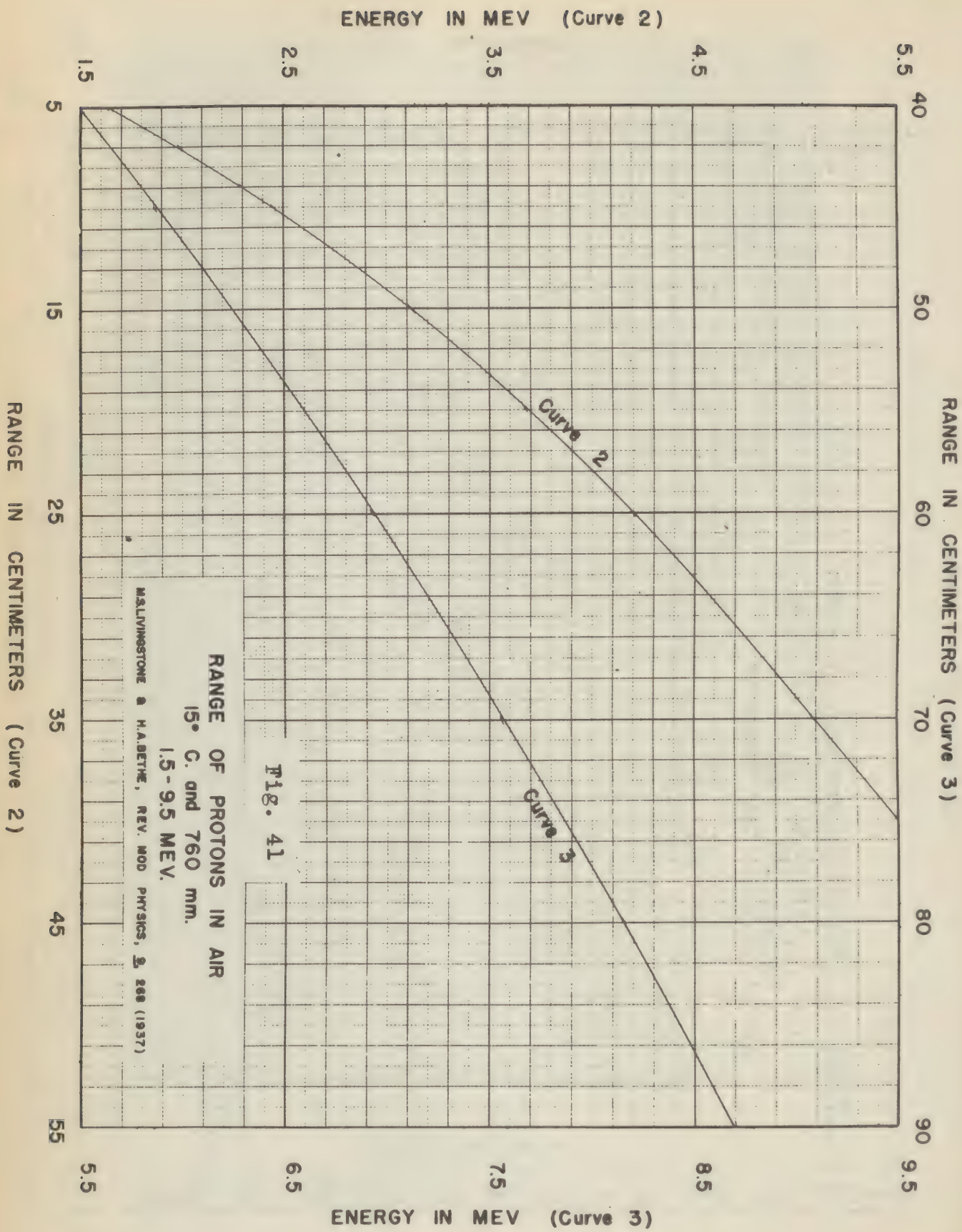
RANGE OF PROTONS IN AIR  
15° C. and 760 mm.

0-2 MEV.

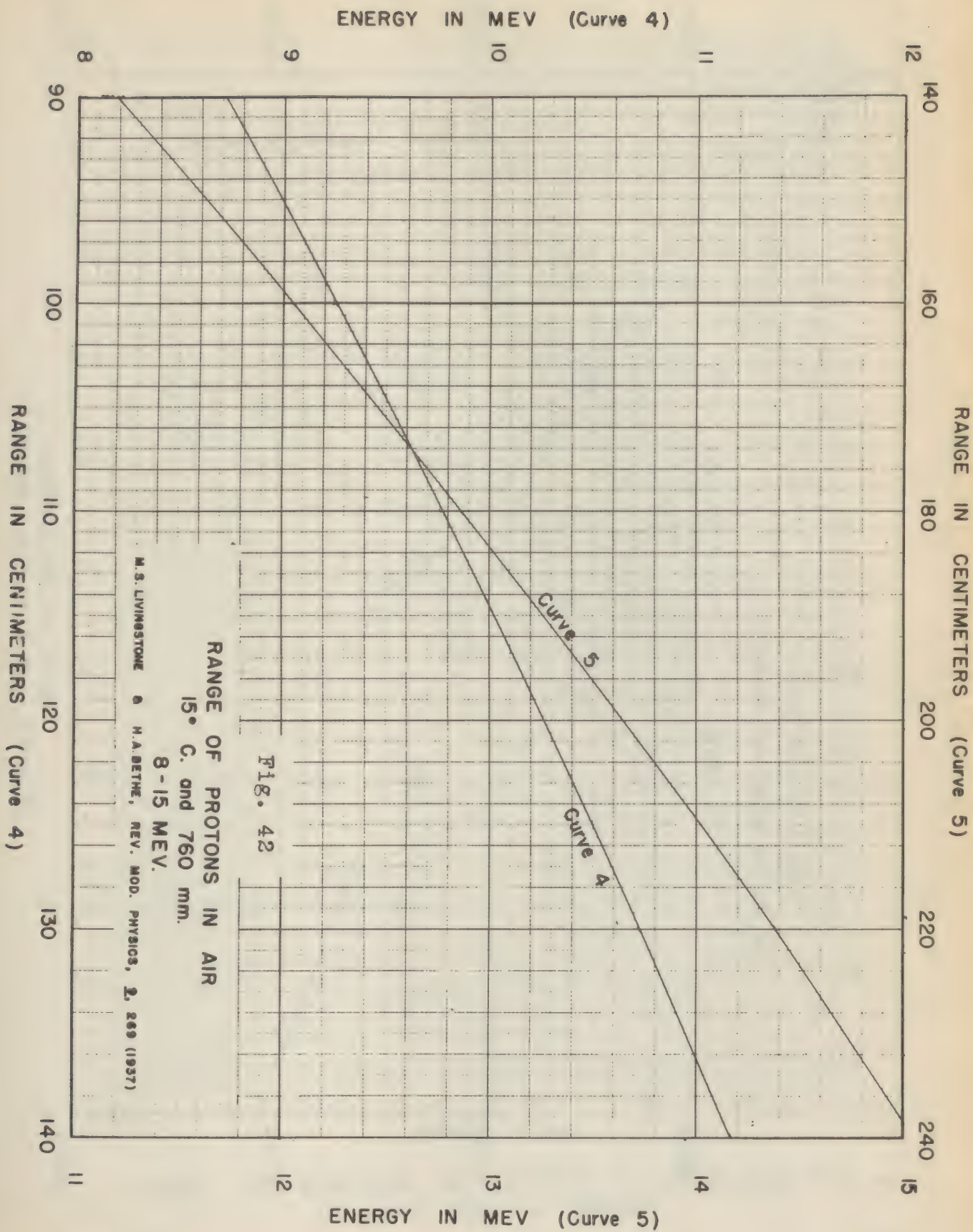
M.S. LIVINGSTONE & H.A. BETHE, REV. MOD. PHYSICS, 2, 268 (1937)

RANGE IN CENTIMETERS

5







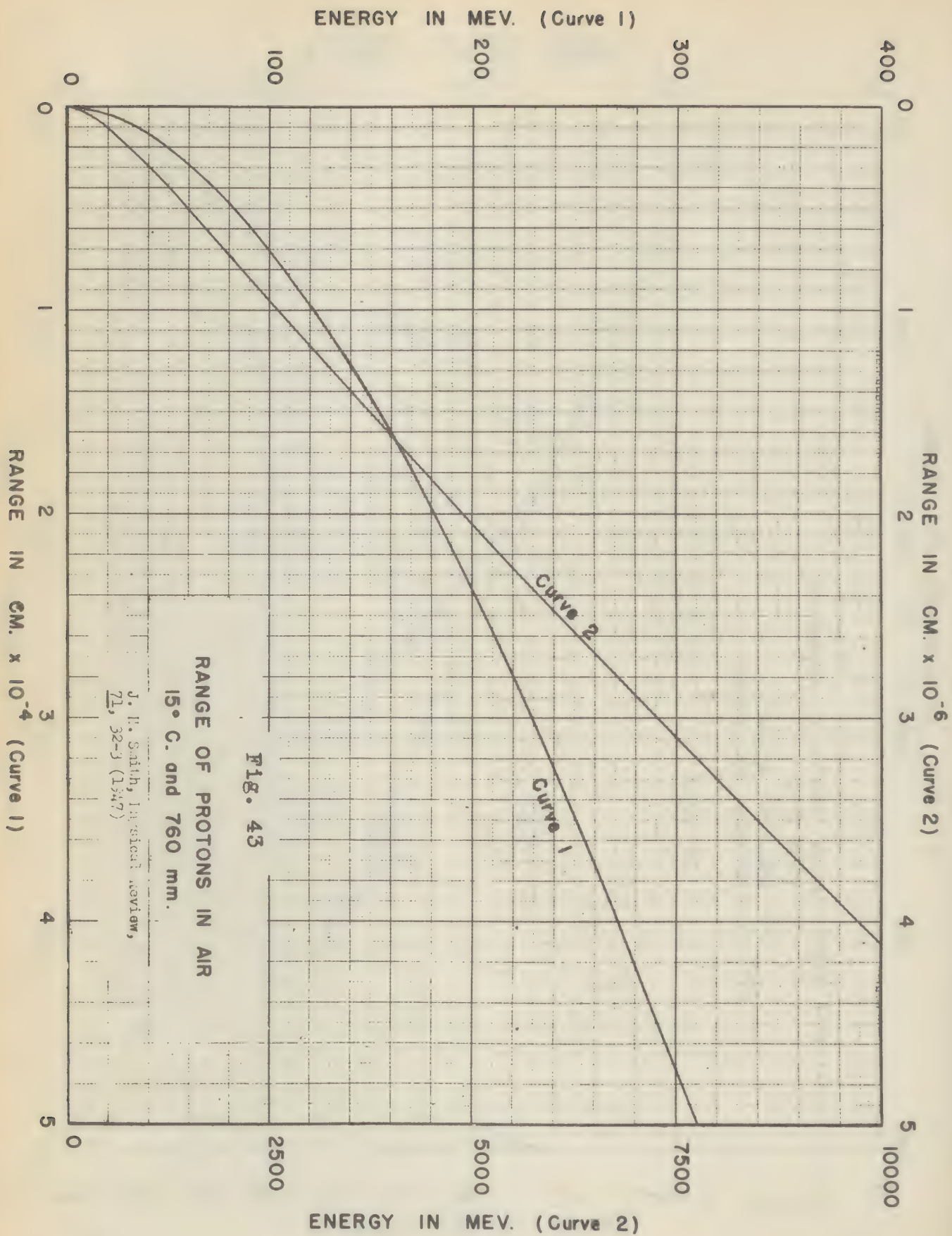


Fig. 43

RANGE OF PROTONS IN AIR  
15° C. and 760 mm.

J. H. Smith, *Physical Review*,  
71, 32-3 (1947)



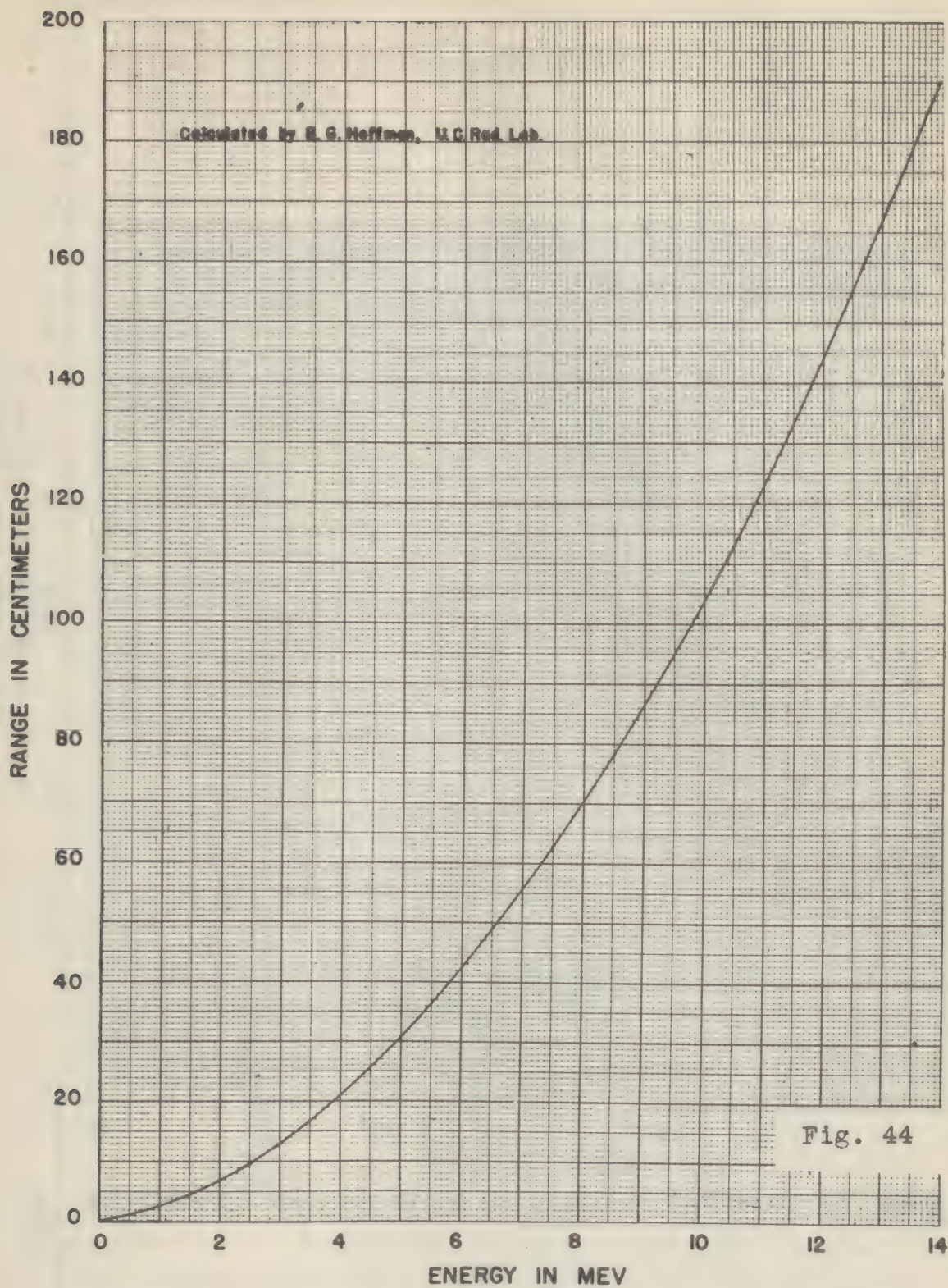
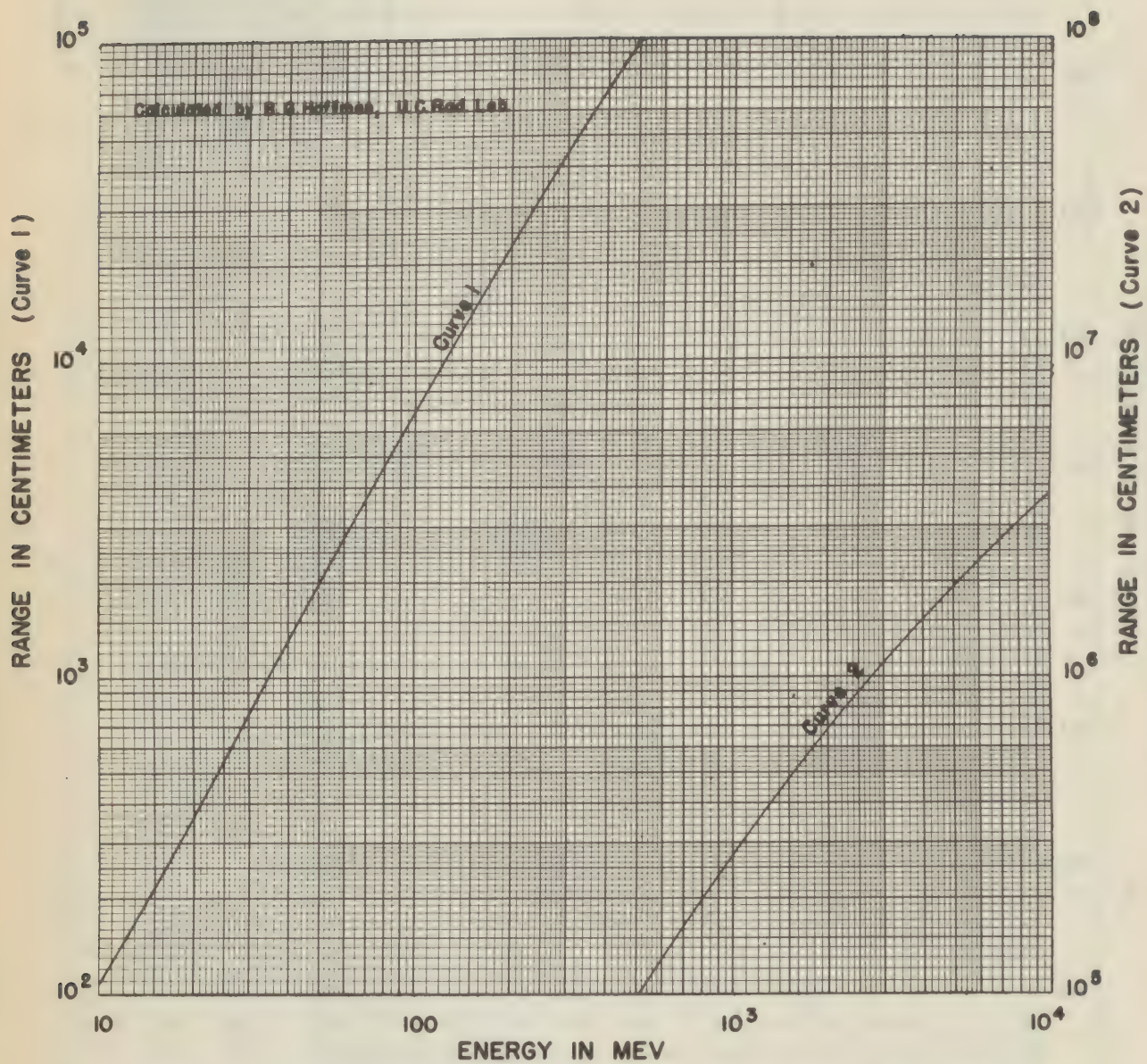


Fig. 44

RANGE OF PROTONS IN OXYGEN AT 15° C. AND 760 mm.

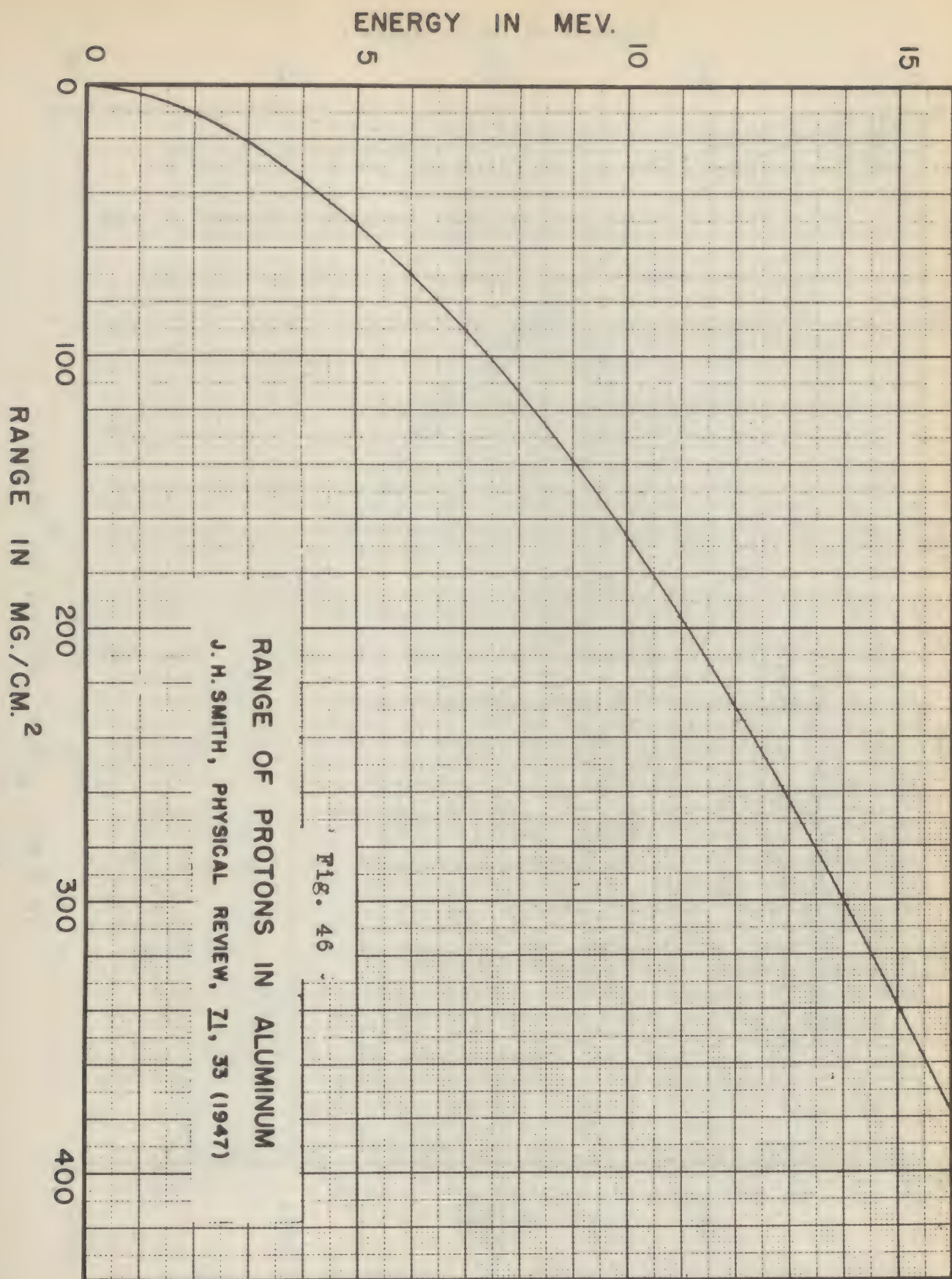


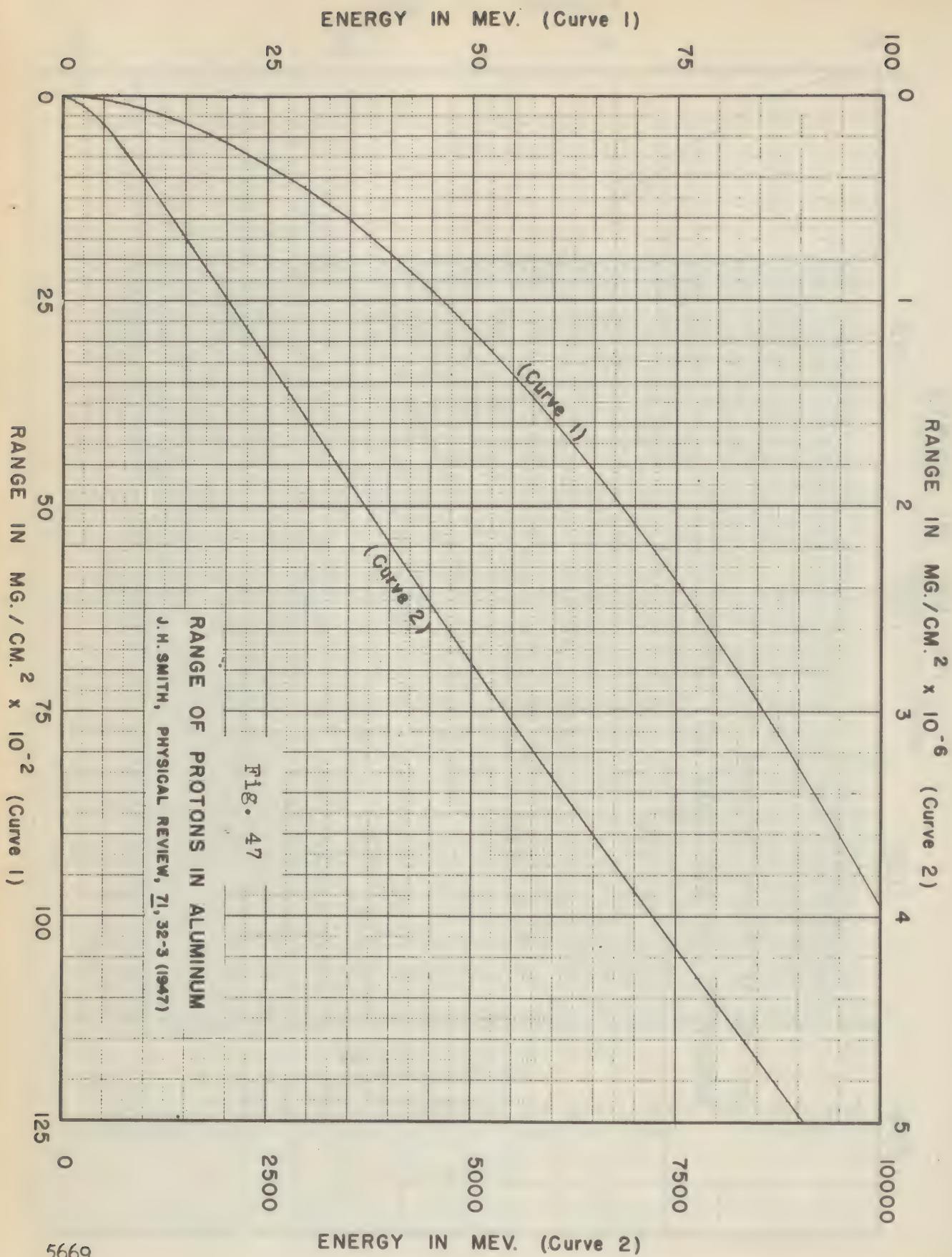


RANGE OF PROTONS IN OXYGEN AT 15° C. AND 760 mm. Hg.

Fig. 45

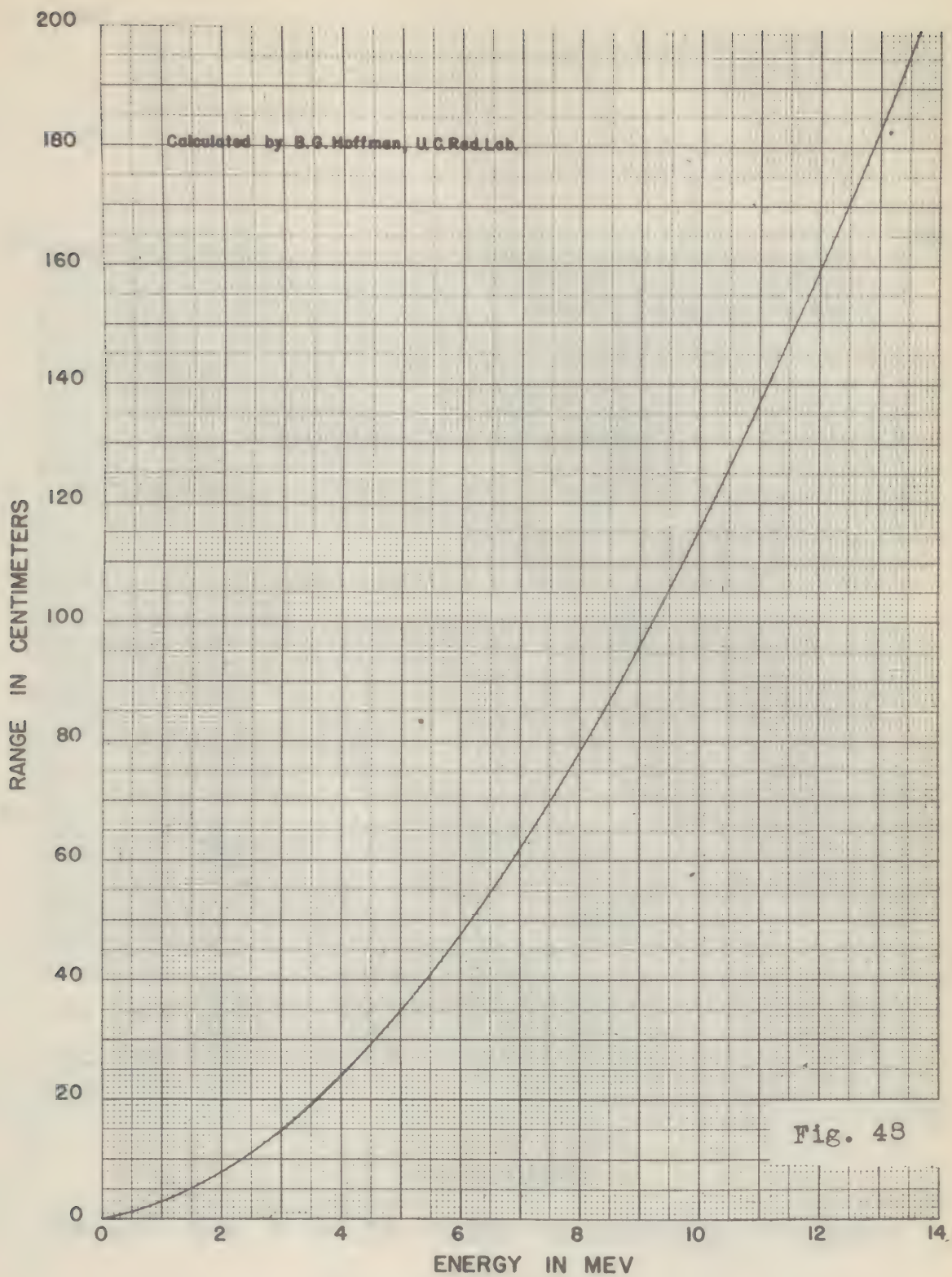




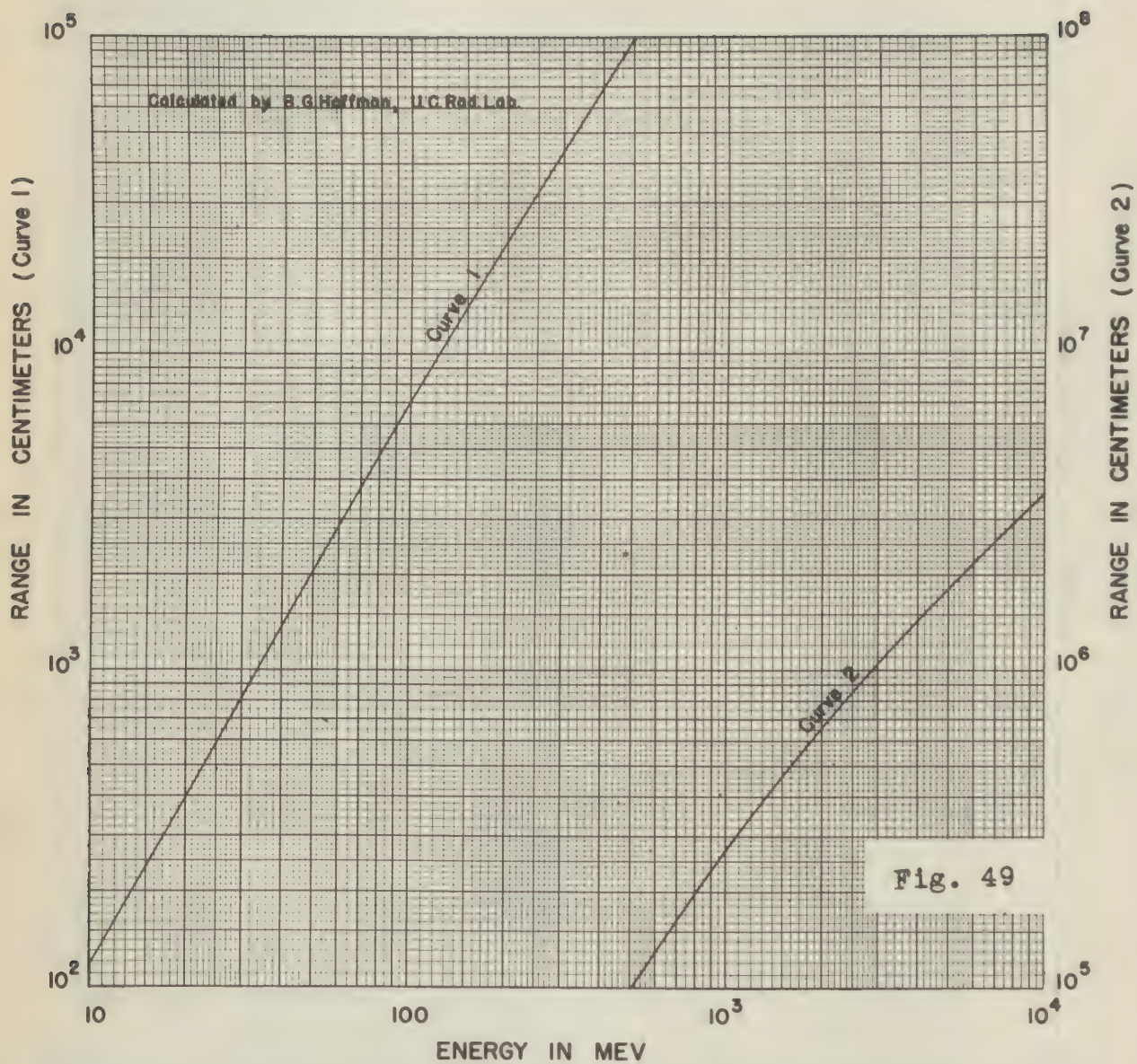


5669



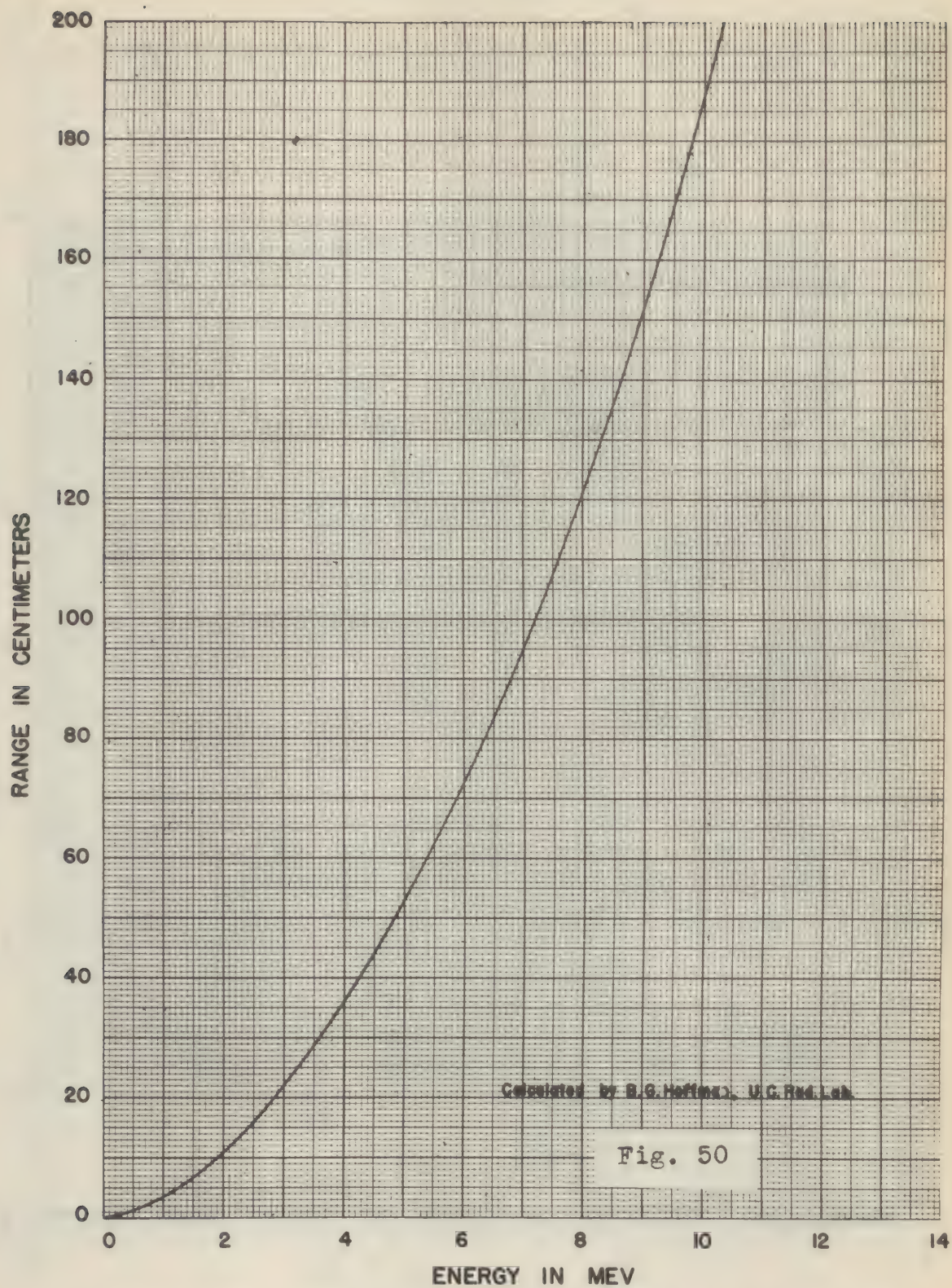


RANGE OF PROTONS IN ARGON AT 15° C. AND 760 mm.



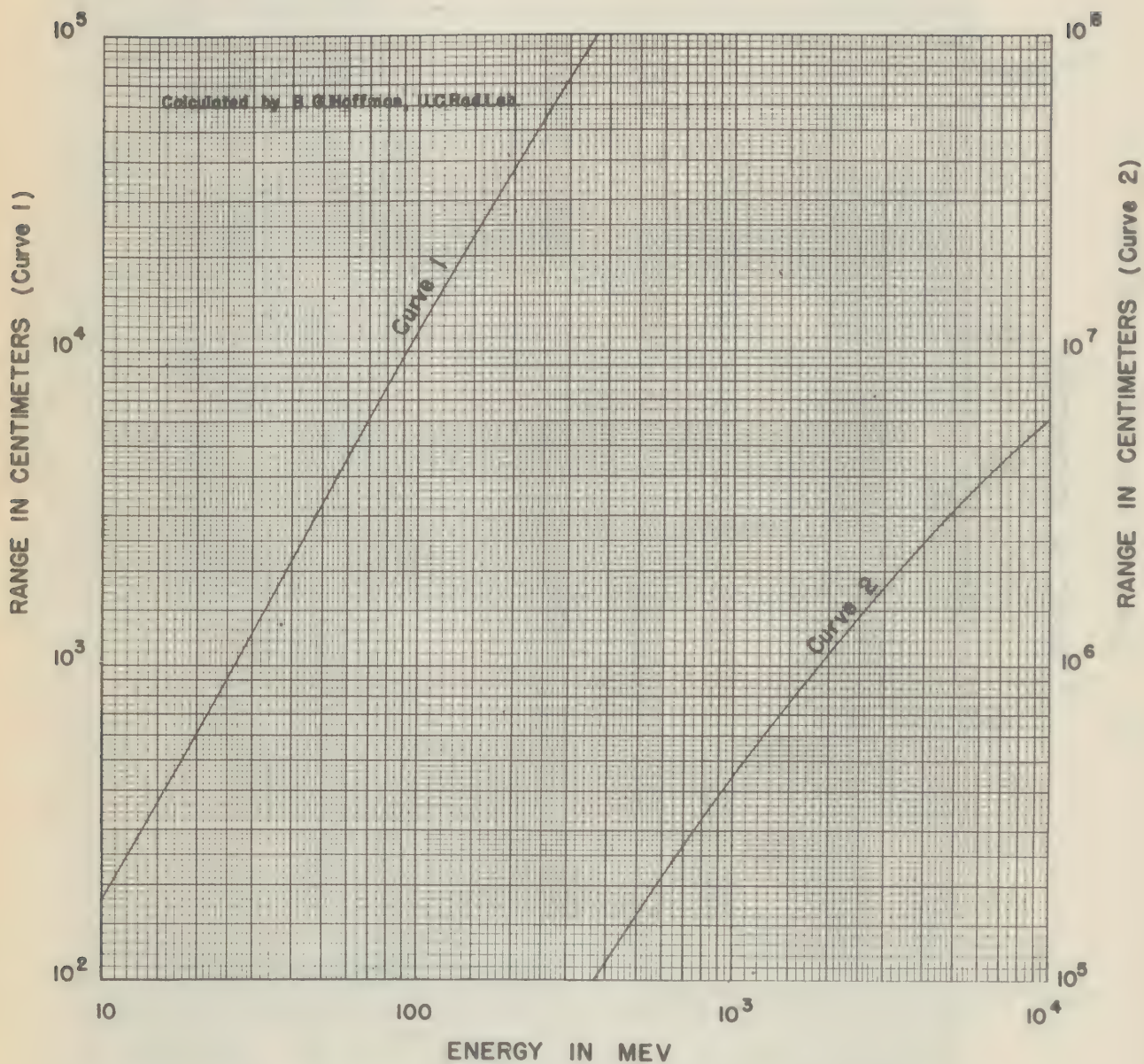
RANGE OF PROTONS IN ARGON AT 15° C. AND 760 mm.





RANGE OF PROTONS IN NEON AT 15° C. AND 760 mm.

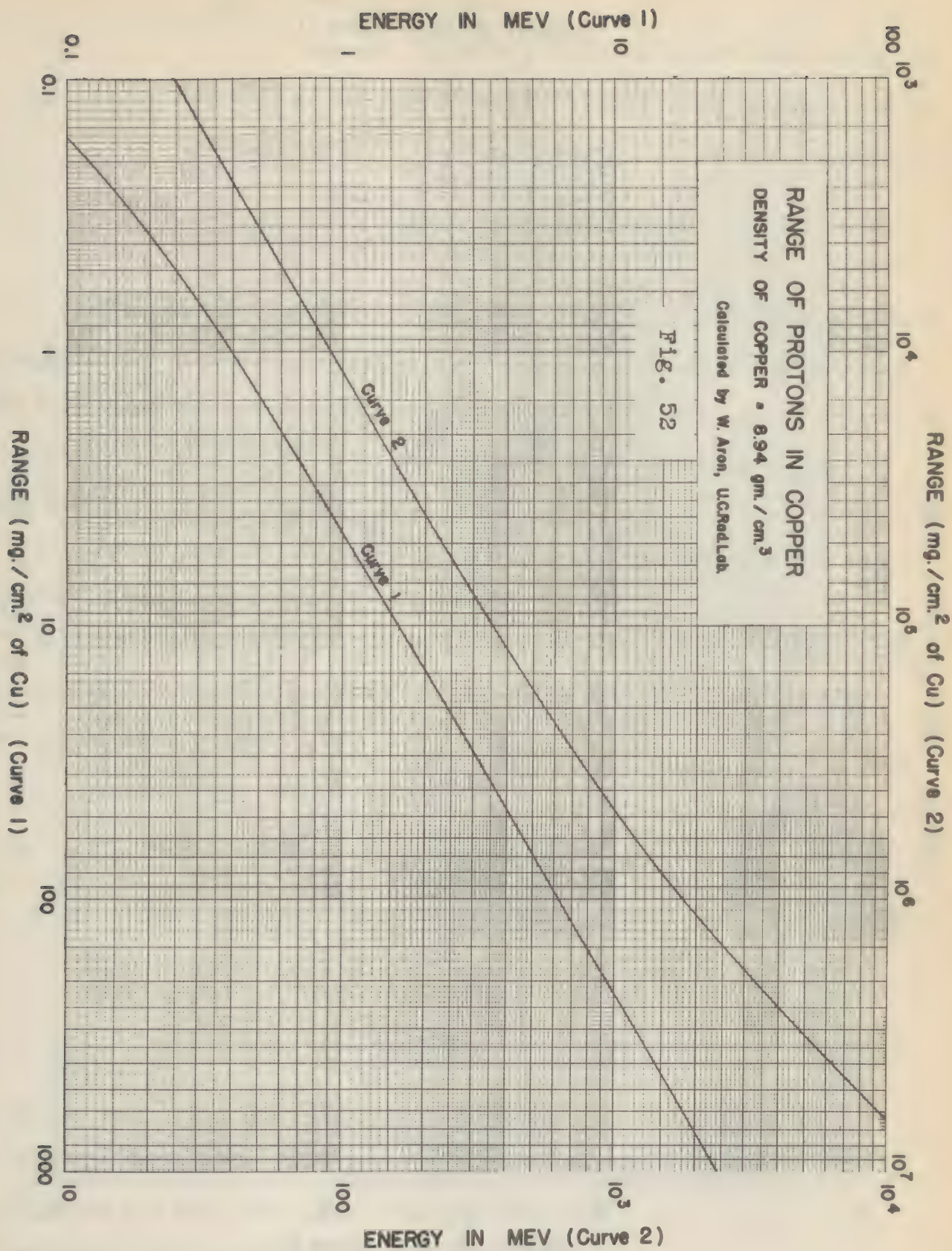


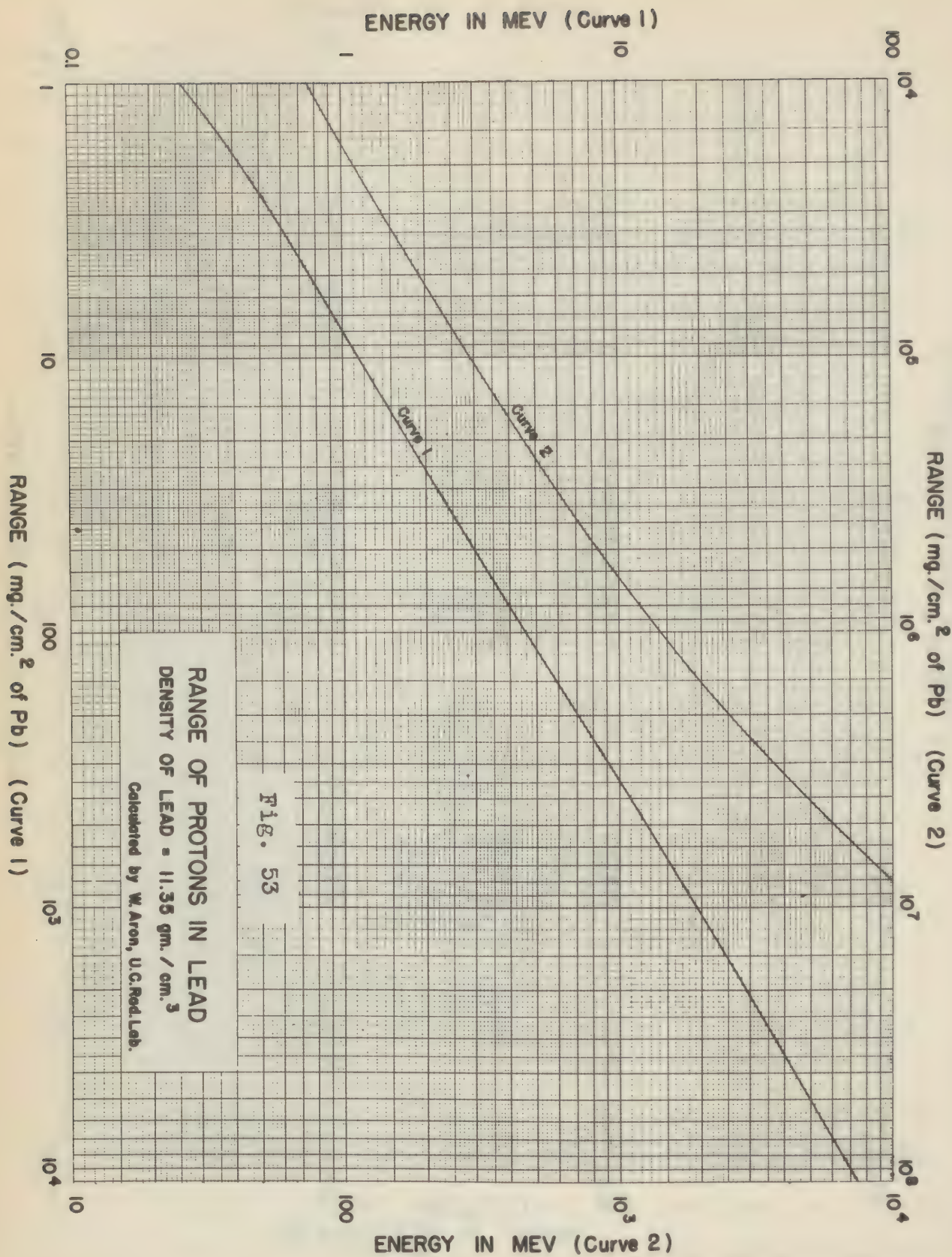


RANGE OF PROTONS IN NEON AT 15° C. AND 760 mm.

Fig. 51









### 8. DEUTERON

mass (neutral): 2.01472

charge:  $(1.60203 \pm 0.00034) \times 10^{-20}$  abs. e.m.u. (1)

magnetic moment :  $+ 0.8565 \pm 0.0004$  nuclear magneton (2)

binding energy :  $2.185 \pm 0.02$  mev (4)

spin: 1

statistics: Bose-Einstein

The interaction of deuterons with matter follows in detail the section on alpha particles when the appropriate deuteron mass and charge are substituted. This introduces only changes in magnitude and the processes of energy loss and scattering together with the range-energy relation are identical to those of alpha particles.

The energy loss of deuterons per cm path is just one-quarter of that for alpha's of the same velocity.

Since the energy varies directly as the mass, the range of deuterons can be obtained directly from the range of alpha particles of the same velocity from the relation

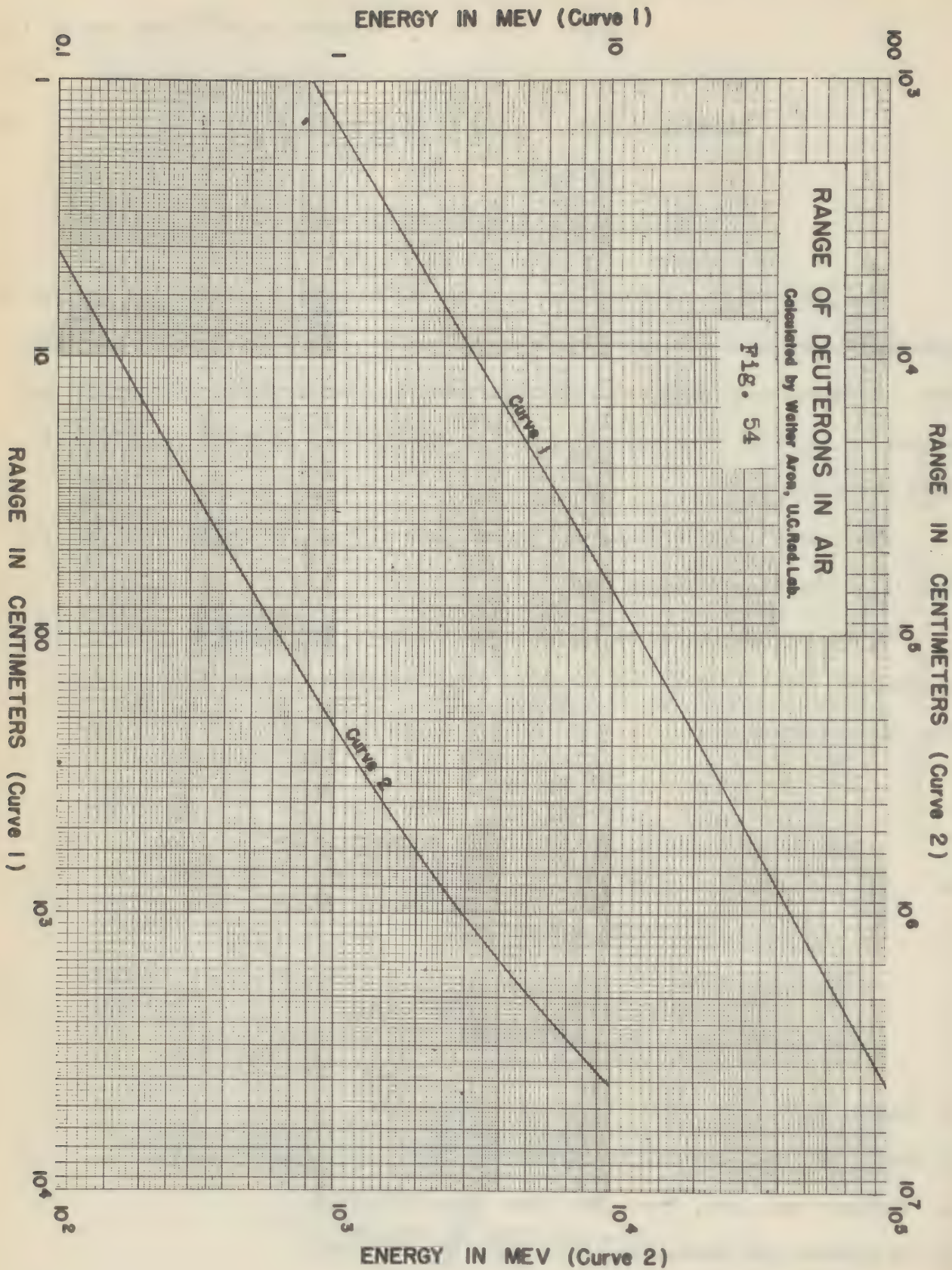
$$R_d = \frac{M_d}{M_\alpha} \frac{Z_\alpha^2}{Z_p^2} R_\alpha$$

or

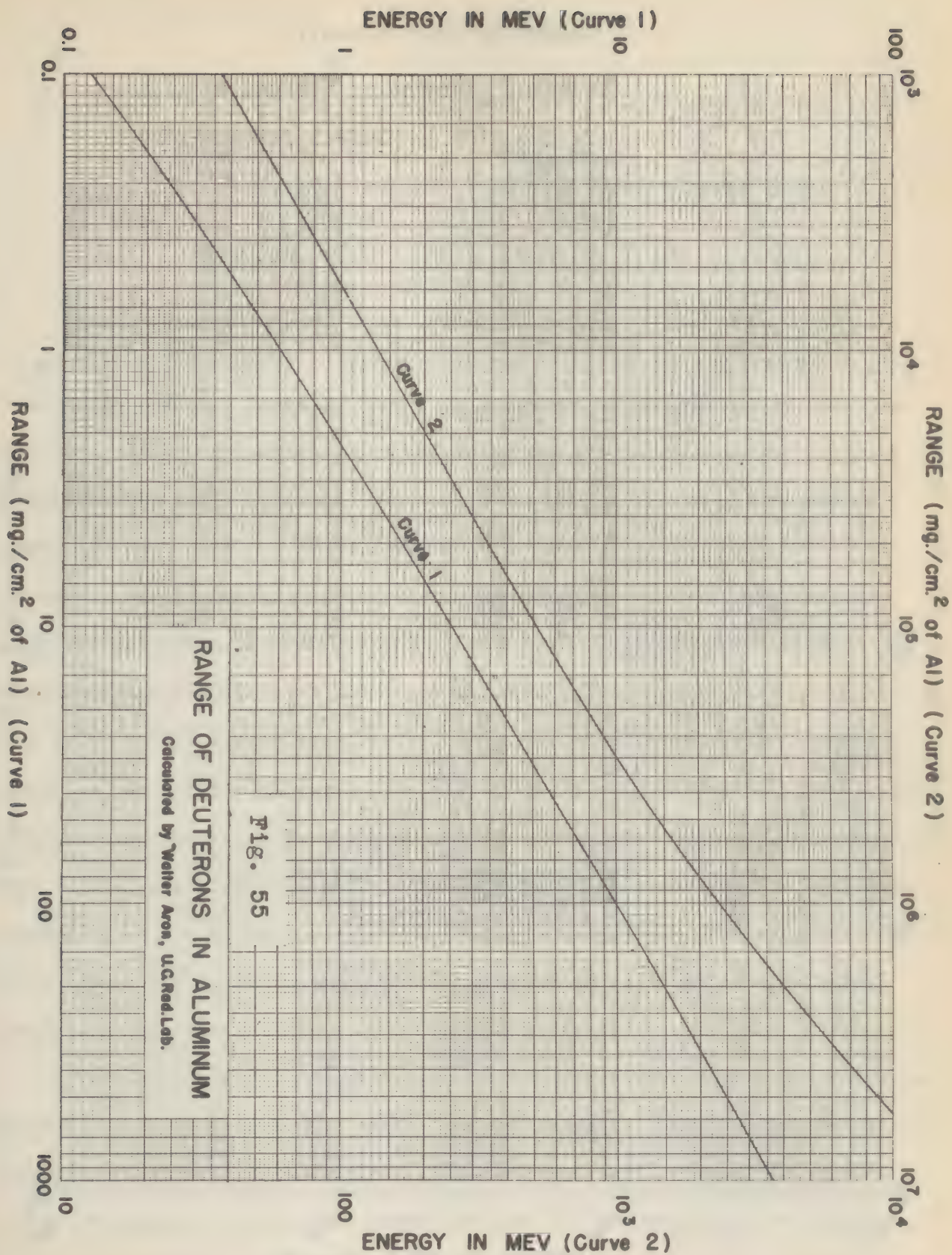
$$R_d = 2.012 R_\alpha$$

#### REFERENCES

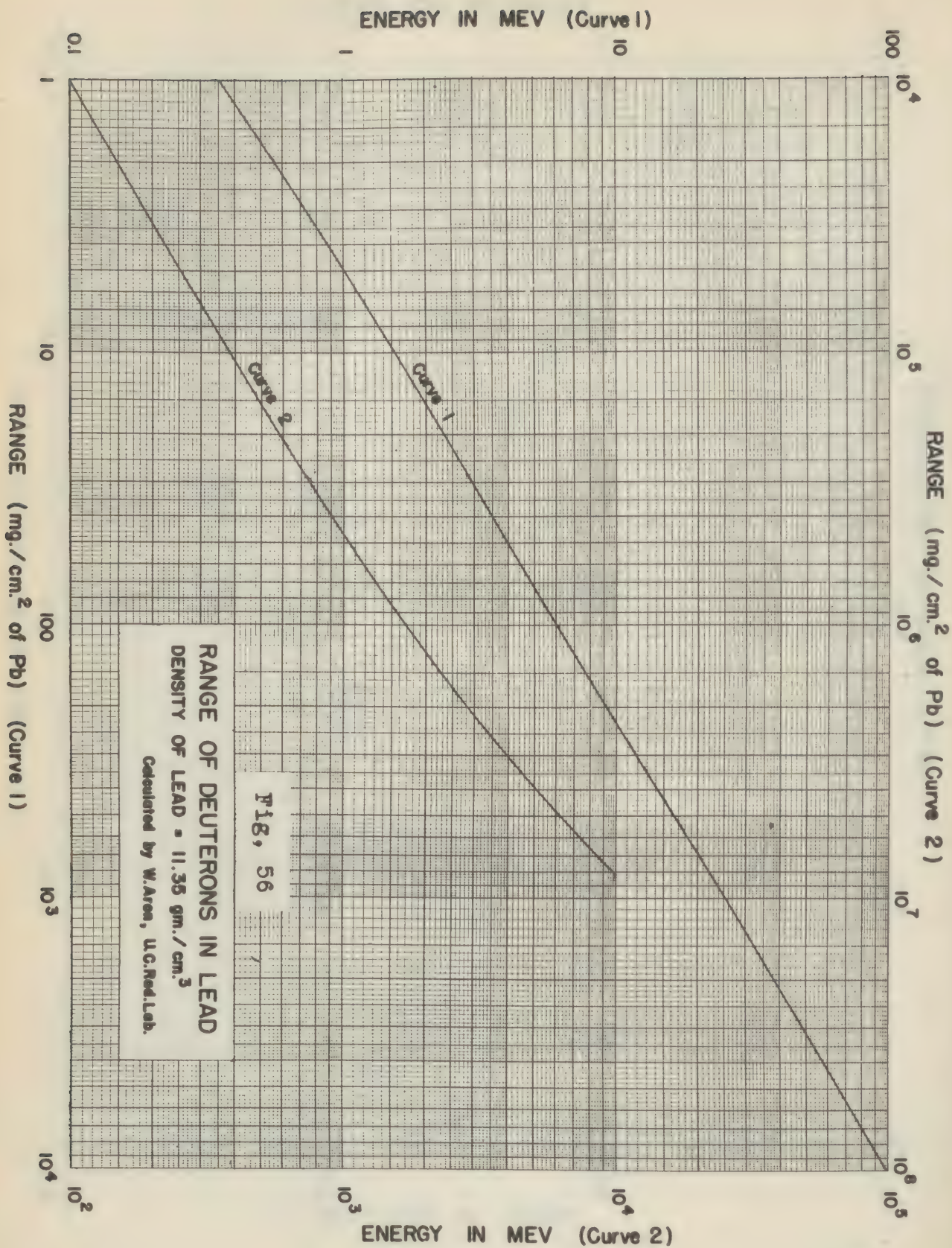
1. Birge, R. T., Rev. Mod. Phys. 13, 233 (1941)
2. Rabi, Kellogg, Ramsey, and Zacharias, Phys. Rev. 56, 728 (1939)
3. Blockett and Lees, Proc. Roy. Soc. 134, 658 (1932)
4. Wiedenbeck and Marhofer, Phys. Rev. 67, 54 (1945)













## 9. NEUTRONS

### A. General Properties

mass:  $1.008937 \pm 0.0000075$  (1)

charge: 0

magnetic moment:  $-1.9103 \pm 0.0012$  nuclear magneton (2)

statistics: Fermi

half-life:  $\sim 20$  min.

The behavior of neutrons in matter is very different from that of charged particles. No range-energy relation can exist since a neutron does not lose energy by ionization or radiation and its interaction with nuclei depends in a very complicated way on its energy and the structure of the struck nucleus. Actual loss of energy can occur only through elastic and inelastic scattering by nuclei but the probability of these processes is, with the exception of hydrogen and a few of the lightest elements, roughly only the same magnitude as those processes in which the neutron is captured ( $\approx 10^{-24}$  cm<sup>2</sup>). Consequently, after traversing even short distances in an absorber, an initially homogeneous beam of neutrons has diminished in intensity through loss of neutrons from capture and has had its energy distributed into a continuous spectrum by the effects of scattering; both processes depending on the energy and on each other. A range-energy relation, therefore, would not properly describe the behavior of neutrons nor can one be computed.

Terms which more adequately describe the behavior of neutrons in matter must necessarily involve the energy and the specific absorber (or scatterer). Principally, these are the probabilities for the various possible interactions with nuclei in terms of cross sections for the processes at different

energies, and the spacial and energy distribution of neutrons in the substance. In the case of diffusion, additional properties are important such as flux, diffusion length, mean free path, and albedo.

The very marked dependence of neutron processes on energy has lead to the universal use of the terms fast, slow, and thermal to indicate broad and rather indefinite energy ranges. Fast neutrons are those with any energy greater than tens of kev; slow neutrons are those which possess energies less than this. Included with the slow neutrons are thermal neutrons which possess only thermal kinetic energies; energies of the order of  $kT$  ( $\sim 0.02$  ev).

Because of their absence of charge, neutrons are unaffected by the Coulomb barriers surrounding nuclei which in the case of charged particles prevents nuclear interaction except at high energies. Neutrons of all energies, down to the slowest thermal neutron, therefore, have free access to the nucleus with which they may form a compound nucleus. The type of reaction which follows the formation of the compound nucleus depends on the initial neutron kinetic energy and the form of the initial nucleus. In all cases, neutron interaction, depending on these conditions, will lead to one of the following processes:

1. Elastic scattering: Initial kinetic energy of the neutron shared by recoil nucleus and scattered neutron; no change in nucleus.
2. Capture: Struck nucleus retains neutron, generally with emission of gamma radiation.
3.  $(n,n)$ : Neutron capture followed by emission of one or more neutrons; special case is elastic scattering; neutron leaves with same energy as initial neutron.
4.  $\left. \begin{array}{l} (n,p) \\ (n,d) \\ (n,\alpha) \\ (n,ap) \end{array} \right\}$  : Neutron captured and one or more charged particles emitted.



5. Fission: Neutron absorbed and compound nucleus splits into two fragments.
6. Other processes are now reported in which very high energy neutrons (~100 mev) totally disintegrate nuclei or lead to the emission of large numbers of particles.

In most instances, several processes are found to compete simultaneously and with probabilities of roughly the same magnitude. In particular, elastic scattering and radiative capture have cross sections of similar magnitude over wide energy ranges in many substances.

Aside from its present important practical applications, such as the chain reacting pile and the production of radioisotopes, the variation in the magnitude of cross sections with energy for the various cross sections provides a convenient means for determining nuclear energy levels. This is possible mainly with slow or thermal neutrons. At these energies, the levels are sufficiently separated so that with beams of monoenergetic neutrons it is possible to detect level differences by the presence of resonances in the incident neutron energies, at which the cross sections for capture and scattering exhibit well-defined peaks; frequently several orders of magnitude greater than the values for off-resonance energies. For low energies and light and medium nuclei, usually a single quantum level is affected by the incident neutron while adjacent levels do not contribute in the formation and disintegration of the compound nucleus. At high neutron energies, well-defined resonance peaks disappear and the cross section, or probability, of the nuclear process decreases relatively uniformly; in most substances as  $1/E$ , where  $E$  is the incident neutron energy. At these energies the spacing (in terms of energy) between levels becomes less than the width of the levels

(width at half maximum value) and, consequently many quantum levels may be involved which effectively contribute to a more complex state of excitation in the compound nucleus. At very high energies where the deBroglie wave length of the neutron becomes smaller than the nuclear diameter, the capture and scattering cross sections remain essentially equal to the geometric cross sectional area and surface area respectively of the nucleus.

The slowing down of neutrons is of the greatest practical importance because all known sources provide only fast neutrons. In some respects the problems it presents are similar to those encountered in the diffusion of ordinary gases, or in the case of slowing by heavy nuclei, the diffusion of electrons in a conductor. The principle problems in both slowing down and thermal diffusion are the neutron distribution in space, i.e., the neutron density, and the energy distribution throughout the diffusing medium.

For a detailed discussion of neutron processes, see: Bethe, H. A., Rev. Mod. Phys. 9, 69 (1937).

#### B. Elastic Scattering of Neutrons

Elastic scattering involves only a redistribution of the initial neutron energy and momentum between the scattered neutron and the recoil nucleus as required by the conservation laws. The nucleus otherwise remains unchanged during the collision and, hence, no energy is lost through excitation. The energy transferred to the recoil nucleus of mass  $M$  is

$$E = 4E_0 \frac{mM \sin^2 \theta/2}{(M + m)^2}$$

$m$  = neutron mass.

$M$  = nuclear mass.

$E_0$  = initial neutron energy.



$\theta$  = deflection angle of neutron from its initial direction with respect to the center of mass.

For a head-on collision ( $\theta = 180^\circ$ ) the neutron loses the greatest energy:

$$E_{\max} = \frac{4mME_0}{(m + M)^2}$$

Thus, in the case of hydrogen ( $m = M$ ), a neutron can lose its entire energy and be brought to rest in a single collision.

The elastic scattering of slow neutrons is given by sum of two processes. The first arises from "potential" scattering for which the cross section is identical to that obtained for the collision of two hard spheres and is equal to the total effective surface area of the struck nucleus. The second term becomes significant when the neutron energy is near resonance with a level of the nucleus. When only one level is affected, as will frequently be the case for slow neutrons, the total elastic scattering cross section is given by the potential scattering and the Breit-Wigner "one-level" formula (3,4)

$$\sigma_{sc} = 4\pi R^2 + \frac{\pi}{2} \left( 1 + \frac{1}{2i + 1} \right) \lambda_r \Gamma_n \frac{4R(E - E_r) + \lambda_r \Gamma_n}{(E - E_r)^2 + 1/4\Gamma^2}$$

$R$  = effective radius of nucleus.

$E_r$  = resonance energy.

$\lambda_r$  = de Broglie wave length of neutron at resonance energy.

$$= (h^2/8\pi^2 \mu E)^{1/2}.$$

$$\mu = mM/(m + M)$$

$\Gamma_n$  = neutron width

$\Gamma$  = total resonance level width

$i$  = angular momentum of nucleus before collision,  
 + sign used if angular momentum of resonance  
 level is  $i + 1/2$ ; - sign if it is  $i - 1/2$ . If  
 $i = 0$  (most even-even nuclei), plus sign is used.

The shape of the cross section curve near resonance is similar to the dispersion curve for light. A maximum occurs at exact resonance and decreases rapidly on either side. On the low energy side, it decreases rapidly to a minimum value before returning to the normal constant value for potential scattering. If the ratio  $\lambda_r \Gamma_n / R \Gamma$  is large, the displacement of the minimum from the exact resonance energy is (2)

$$E_r - E_{\min} = \lambda_r \Gamma_n / 2R$$

The relative magnitude of potential and resonance scattering is seen from the ratio of total cross section at exact resonance to the cross section for only potential scattering ( $\sigma_p = 4\pi R^2$ ):

$$\frac{\sigma}{\sigma_p} = 1 + 1/2 \left( 1 \pm \frac{1}{2i + 1} \right) \frac{\lambda_r \Gamma_n}{R \Gamma}$$

When  $\lambda_r \Gamma_n \ll R$  only potential scattering is at all important. This appears from experimental evidence to be the case for nearly all substances with only a few exceptions, e.g., Ag. In general, therefore, resonance scattering is small or negligible, and the cross section nearly constant with respect to the neutron energy.

In most nuclei, elastic scattering is obscured by competing and more probable capture processes. Only in the light elements, excepting Li6, B10, N14, and in a few of the medium weight elements are the elastic cross sections larger than capture. Hydrogen exhibits the largest cross section;  $12 \times 10^{-24} \text{ cm}^2$ .



### C. Interaction of Slow Neutrons with Nuclei

The interaction of neutrons with nuclei involving the process of capture, formation of a compound nucleus, and the subsequent emission of radiation was first treated by Breit and Wigner for the case where only one nuclear resonance level was important in the process (3). This was later extended to the more general problem by Bethe and Placzek (5) and others (6,7,8,9).

If only one level is important in the interaction process because of the wide spacing of levels in the energy range to which a slow or thermal neutron can excite the nucleus. then the cross section for the formation of a compound nucleus and the emission of a particle ( or gamma ) of the kind q is given by the one-level formula in the form

$$\sigma_q = \frac{\pi}{2} \left( 1 + \frac{1}{2i + 1} \right) \frac{\lambda \lambda_r \Gamma_n \Gamma_q}{(E - E_r)^2 + 1/4 \Gamma^2}$$

$\lambda$  = de Broglie wave length of neutron.

$\lambda_r$  = de Broglie wave length at resonance.

$E$  = neutron energy.

$E_r$  = resonance energy.

$\Gamma_n$  = neutron width.

$\Gamma_q$  = width for emitted particle ( or gamma ray ).

$\Gamma$  = total width for all processes.

The total width,  $\Gamma$ , includes all possible processes summed over their widths. This includes neutron emission, gamma ray and charged particle emission as well as fission. Since the neutron width varies as  $E^{1/2}$ , the total width can be written in the form

$$\Gamma = \Gamma_n (E/E_r)^{1/2} + \sum_q \Gamma_q$$

Ordinarily, for slow neutrons, only one kind of particle has a high probability for emission and the contributions of other processes to  $\Gamma$  is negligible. Furthermore, the emission of a neutron (inelastic scattering) is important only when simple capture with gamma emission is unlikely and when the emission of a charged particle is energetically impossible because of the potential barrier. But usually,  $\Gamma_n \ll \Gamma_q$  as seen from the fact that the observed ratio for these two widths is  $\sim 10^{-3}$ . Therefore, the total width in many instances can be set equal to the particle width;  $\Gamma = \Gamma_q$ . In individual cases, the relative magnitude of the neutron width can be determined experimentally from the cross section at exact resonance since it is then directly proportional to the ratio  $\Gamma_n/\Gamma$  .i.e.,

$$(\sigma_n)_r = \frac{\pi}{2} \chi_r^2 \left( 1 + \frac{1}{2i + 1} \right) \frac{\Gamma_n}{\Gamma}$$

From the one-level formula for elastic scattering and the similar formula above for capture, the ratio of the two cross sections gives the relative probability at resonance for elastic scattering (neglecting potential scattering) with respect to a competing capture process (with particle or gamma emission):

$$\frac{\sigma_{sc}}{\sigma_q} = \frac{\Gamma_n}{\Gamma_q} \left( \frac{E}{E_r} \right)^{1/2}$$

This ratio is greater than unity for most of the light elements (except Li 6, B 10) and in general, less than unity for elements of medium atomic weight (except Fe, Ni, Cu).

The emission width,  $\Gamma_q$ , for charged particles is the product of the particle width without the potential barrier,  $\Gamma'_q$ , and the penetrability,  $P$ , of the barrier, i.e.,  $\Gamma_q = \Gamma'_q P_q$ , where  $P_q = e^{-f}$  (see: Alpha Decay). Because of the factor  $P$ , charged particle emission is all but the lightest elements



and in the special case of fission, is extremely improbable under slow neutron bombardment. Proton emission is known only for N 14 although it is energetically possible for B 10 (4). Alpha particle emission is observed only in Li 6 and B 10 which have very large crosssections; 3000 and 900 barns respectively. The total kinetic energies released in these two processes (alpha plus recoil nucleus) are 4.6 and 3.0 mev respectively.

Without a more exact and detailed model for the nucleus, the most probable process and its width must be determined experimentally. In general, it will include any one of the processes (n,n), (n,p), (n, $\alpha$ ), (n, $\gamma$ ) and fission.

If the energy of the neutron is small compared to the first resonance level, or if it is small compared to the width of the first level, i.e.,  $E \ll E_r$  or  $E \ll \Gamma$ , then the resonance terms become unimportant and the cross section for capture varies directly with  $\lambda_r$ , or as  $1/v$ , where  $v$  is the neutron velocity. This is observed most clearly in Rh, In, and Ir for thermal neutrons, and for B 10 for energies up to  $\sim 0.1$  mev.

#### D. Interaction of Fast Neutrons with Nuclei

The interaction of fast neutrons with nuclei involves a single nuclear energy level only when the level spacing is comparable with the total neutron energy. This is sometimes the case for light elements and for energies up to  $\sim 1$  mev; corresponding excitation energies of the order of 7 - 8 mev. In medium and heavy nuclei and for higher energies and light nuclei, more than one level is excited in the formation of the compound nucleus and in the subsequent emission of radiation (gamma, neutron, or charged particle), and the one-level formula is then not valid. When the levels are closely spaced, an average cross section for a particular process is obtained by summing the one-level formula over all states of the final nucleus. If it can be

assumed that the average level spacing is small, i.e., the level density is high, instead of summing, the averaging can be performed by integrating over an energy range large, compared to the level spacing but small compared to the neutron kinetic energy. The average cross section for the capture of fast neutrons and emission of a particular radiation  $q$  is given by

$$\sigma = \pi R^2 \xi \frac{\Gamma_q}{\Gamma}$$

$R$  = nuclear radius.

$\Gamma_q$  = particle, radiation, or fission width.

$\Gamma$  = total width for all processes.

$\xi$  = sticking probability.

Further, the total average cross section for any and all processes,  $q$ , which can occur,  $(n,n)$ ,  $(n,\gamma)$ ,  $(n, \text{charged particle})$ , fission, etc., is found by summing over the width for all processes:

$$\sigma = \pi R^2 \xi$$

The sticking probability,  $\xi$ , as used here, is defined as the probability that a neutron which strikes a nucleus will stick, i.e., be absorbed to form a compound nucleus. For high excitation energies where the nuclear level spacing is small this is roughly  $\xi = \Gamma_n/D$ , where  $\Gamma_n$  is the neutron width and  $D$ , the average level spacing. For high energy neutrons and particularly in medium and heavy elements, the sticking probability is nearly unity. For medium energies, ~1 mev, it appears to be of the order of 0.1 and for low energies, considerably less (4). At very high energies, therefore, the total cross section, or if only one process is important, then its cross section, is just equal to the geometric cross sectional area of the nucleus,  $\pi R^2 (\sim 10^{-25} \text{ cm}^2)$ .



This, necessarily, corresponds to energies for which the neutron wave length is less than the nuclear radius.

Brief descriptions of the separate processes are given below.

### 1. Inelastic scattering (n,n).

The emitted neutron is ejected with less kinetic energy than the initial neutron. Only in the event that the nucleus is left in the ground state are the two neutrons energies equal; in which case the process is similar to elastic scattering. In inelastic scattering, the difference between the energies of the initial and emitted neutrons is contributed to the excitation of the residual nucleus and is subsequently emitted as gamma radiation. The direction taken by the ejected neutron is purely random since, in effect, the nucleus does not remember the direction of incident neutron. Such neutrons, therefore, are observed to be emitted uniformly over a sphere. Also it is to be noted that the energy and momentum laws for the collision of hard, spherical particles does not hold since part of the energy is lost to excitation.

If the incident neutron energy is less than the lowest nuclear level, only elastic scattering can occur, i.e., for slow or thermal neutrons. On the other hand when the energy is sufficiently high to excite many levels, a neutron may be emitted by any one of many possible level transitions and the observed energy distribution of the neutrons is approximately Maxwellian (8).

The observed (n,n) cross section for fast neutrons is found, in many substances, to be a large fraction of the total cross section for all possible processes.

### 2. Radiative Capture (n, $\gamma$ ).

Since inelastic scattering is known to occur in most instances with an appreciable probability, if it is assumed that this and radiative capture are

the only possible process in a particular nucleus, the cross section for  $(n,\gamma)$  is

$$\sigma_{(n,\gamma)} = \pi R^2 \xi \frac{\Gamma_\gamma}{\Gamma_n + \Gamma_\gamma}$$

The gamma width,  $\Gamma_\gamma$ , does not appear to be a sensitive function of the neutron energy and has a value ranging from 0.1 to 1.0 ev for slow neutrons which is assumed to be roughly the same for neutron of medium energy; 10-500 kev. Bethe (4) gives for the average capture cross section, the expression

$$\sigma_\gamma = 2 \times 10^{-22} E^{-1/2}$$

At very high energies, the radiative capture cross section becomes exceedingly small and multiple neutron and charged particle emission become far more probable.

### 3. Multiple neutron emission $(n,2n)$ , $(n,3n)$ , etc.

More than one neutron is emitted provided the nucleus is left in a sufficiently excited state following emission of the first neutron, i.e., if

$$E_b < E_n - E_e$$

$E_b$  = binding energy of second neutron to nucleus.

$E_n$  = energy of initial neutron.

$E_e$  = energy of first emitted neutron.

Assuming the energy distribution of the emitted neutrons can be approximated by a Maxwell distribution for a temperature  $T$ , the cross section for emission of two neutrons is given by the expression

$$\sigma_{(n,2n)} = \pi R^2 \xi \left( 1 - \left[ 1 + \frac{E_n - E_b}{T} \right] e^{-\frac{E_b - E_n}{T}} \right)$$



$R$  = nuclear radius.

$E_n$  = energy of incident neutron.

$E_b$  = binding energy of neutron to nucleus.

$T$  = absolute temperature correlated to observed energy distribution, or  $T = 2\left(\frac{5E_n}{A}\right)^{1/2}$  mev.

$\xi$  = high neutron energies sticking probability,  
 $\sim 1.0$ .

At very high energies,  $E_n - E_b \gg T$ , the  $(n,2n)$  is dominant and  $(n,n)$  smaller. The process involving the emission of more than two neutrons becomes increasingly more important at very high energies, i.e.,  $E_n \gg E_b$ .

#### 4. Charged particle emission $(n,p)$ , $(n,d)$ , $(n,\gamma)$ , etc.

Reactions leading to the emission of charged particles are probable only when the incident neutron energy is sufficiently high so that the available energy is great enough to allow a charged particle to pass over the electrostatic potential barrier. Assuming the average cross section for high energies to be of the form

$$\sigma = \pi R^2 \xi \frac{\Gamma_q}{P} \quad (\xi \sim 1.0)$$

the charged particle width is the product of the emission width without the barrier,  $\Gamma_q'$ , and the penetrability factor  $P = e^{-f}$  (see: Alpha Decay). Because of the large numbers of levels excited by neutrons with energies high enough to result in charged particle emission, the energy distribution of the emitted particles is continuous and probably roughly Maxwellian.

Ordinarily, the cross section for charged particle emission is small because of the strong competition from the more favorable  $(n,n)$  process or at very high energies, from  $(n,2n)$ ,  $(n,3n)$ , etc.

## 5. Fission

See section on Fission.

## 6. Other processes.

At energies of the order of 100 mev and greater, neutron bombardment frequently leads to the emission of great numbers of particles and probably complete disintegration of nuclei. Such processes are still under investigation at the present time (184 inch synchro-cyclotron at the Radiation Laboratory of the University of California).

### E. Reflection of Slow Neutrons

The scattering of slow neutrons into angles greater than  $90^\circ$  from the initial direction of the beam is usually given in terms of a reflection coefficient defined as the ratio of the number of neutrons scattered back ( $> 90^\circ$ ) to the number scattered forward ( $< 90^\circ$ ). In the general case, the reflection coefficient for a scatterer is (4)

$$R = \frac{s(1 - e^{-2\gamma d})}{2a + s - 2\gamma - (2a + s - 2\gamma)e^{-2\gamma d}}$$

$s$  = scattering coefficient

$a$  = absorption coefficient

$d$  = absorber thickness

$$\gamma = (a^2 + as)^{1/2}$$

Two cases are of special interest in which this reduces to simpler forms:

a. Thin scatterers;

$$R = 1/2 \, sd$$

b. Thick scatterers(10);

$$R = \frac{s}{2a + s + 2\gamma}$$



Measurements of R for thick scatterers provides a direct means for determining the ratio of the scattering cross section to absorption cross section since  $s/a = \sigma_s/\sigma_a$ .

### F. Diffraction of Neutrons

The scattering of slow neutrons by crystals is, in many respects, similar to the behavior of x-rays. This follows immediately from the absence of electrical charge associated with the neutron and the interference phenomena to be expected since the de Broglie wave length of slow neutrons lies in the x-ray region i.e., is comparable to interatomic distances. However, there are three important differences between neutron and x-ray diffraction: 1. the phase angle between scattered and incident wave may be either  $0^\circ$  or  $180^\circ$ ; 2. scattering does not vary regularly with atomic number; 3. absorption is very different from x-rays.

Theoretical treatments of diffraction, reflection, and refraction of slow neutrons have been given by Fermi (11,12), Wick (13), Schwinger and Teller (14) and by Goldburger and Seitz (15). The principle conclusions are given below.

Elastic scattering of slow neutrons, which can be regarded as spherically symmetrical about a scattering nucleus, is given by a wave function at large distances from the nucleus which is the sum of a plane incident wave and a spherically symmetric scattered wave

$$= e^{-ikx} + a \frac{e^{-ikr}}{r}$$

$k = 2\pi/\lambda$  = wave number

$x$  = coordinate normal to incident wave

$r$  = position vector from nucleus

$a$  = scattering length

The scattered wave amplitude,  $a$ , has the unit of length and in the simplest case of elastic scattering leads to a cross section of the form  $\sigma = 4/a^2$ . Because of ( ) above,  $a$ , is negative for 180° phase shift and positive for a zero degree shift (12).

An expression for "a" was given by Goldberger and Seitz (15) for the general case of absorption and scattering which has the form

$$A = \frac{1}{2ik} \sum_n (2n+1) (e^{2i(n)} - 1) P_n(\cos \theta)$$

$R$  = wave number

$P_n$  = Legendre polynomial of order  $n$ .

$(n) = \gamma + i$  = complex phase shift (real for case of absorption)

The absorption, scattering, and total cross section, assuming small phase changes, are then

$$\sigma_a = \frac{4}{R^2} \sum_n (2n+1) \gamma(n) (1-2 \gamma(n))$$

$$\sigma_s = \frac{4}{R^2} \sum_n (2n+1) (\gamma^2 + i^2)$$

$$\sigma_t = \frac{4}{R^2} \sum_n (2n+1) (\gamma^2 + i - i^2)$$

In most cases, absorption is negligible and

$$\sigma_s = \sigma_t = 4/a^2$$

in which  $a$  can be determined from experiment.

These expressions apply strictly only to free atoms of a single species with spin zero. In general, the application to crystals involves the following corrections.



1. Correction for reduced mass of nucleus bound in a crystal:

$$a = \frac{A + 1}{A} a_f$$

$A$  = atomic weight

$a_f$  = scattering length for free atom

2. Corrections for isotope concentration:

$$a = \sum_i P_i a_i$$

$P$  = fractional abundance of isotope,  $i$

$a$  = scattering length of isotope,  $i$

3. Correction for spin,  $I$ , of nucleus when different from zero.

Effective scattering length is:

$$a = \frac{I}{2I + 1} a_I - 1/2 + \frac{I + 1}{2I + 1} a_I + 1/2$$

$a_I + 1/2$  = scattering length for neutron spin  
parallel to nuclear spin

$a_I - 1/2$  = scattering length for neutron spin  
oriented anti-parallel to nuclear spin

Experimental values of the scattering length,  $a$ , given by Fermi (12)  
are presented in the table below.

Table 9. SCATTERING LENGTHS FOR  
SLOW NEUTRONS (12)

Element	a x 10 <sup>12</sup>	$\sigma_{sc}$ x 10 <sup>24</sup>
Ba	0.79	8
Be	.89	6.1
Br	.56	<7
C	.67	4.8
Ca	.79	9.5
Cl	1.13	15
Cu	.81	7.2
F	.60	4.1
Fe	.82	9.2
H	-.39	21.
I	.36	1.6
K	.35	1.5
Li	-.59	--
Mg	.56	4.
Mn	-.44	2.4
N	.87	8.3
Na	.56	3.5
Ni	1.09	13.
O	.61	4.1
Pb	.48	10
S	.28	1.1
Zn	.58	3.6



## G. Laue - Bragg Reflection

When slow neutrons are polarized normal to the plane of incidence, reflection from crystals is analogous to that of X-rays and like X-rays, is determined by the Bragg condition (16):

$$n \lambda = 2d \sin \theta$$

$d$  = lattice plane spacing.

$\theta$  = angle of incidence.

$n$  = order of reflection.

$\lambda$  = wave length.

The intensity of the different orders for crystals consisting of several kinds of atoms is given by the form factor:

$$F = \left| \sum_i a_i e^{\frac{2\pi i n \delta_i}{d}} \right|$$

$a_i$  = scattering length for atom  $i$ .

$\delta_i$  = perpendicular distance of atom  $i$  to plane of reflection.

$d$  = lattice plane spacing.

$n$  = order of reflection.

The depth of penetration of a wave reflected from a crystal according to the Bragg condition is (15)

$$\frac{1}{t} = \frac{4\pi N_0 \sin \theta}{2k} \sum_i \left[ \frac{ik(\sigma_a)_i}{4\pi} + \sqrt{\frac{(\sigma_s)_i}{4\pi} + \left( \frac{k(\sigma_a)_i}{4\pi} \right)^2} \right] e^{-ik \cdot r_i}$$

$k$  = wave number.

$N_0$  = number of cells per unit volume of crystal.

$(\sigma_s)_i$  = scattering cross section for  $i^{\text{th}}$  atom.

$(\sigma_a)_i$  = absorption cross section for  $i^{\text{th}}$  atom.

$\underline{K}$  = reciprocal vector for reflection plane.

$\underline{r}_i$  = position vector for  $i^{\text{th}}$  atom.

For non - absorbing, monatomic crystals this reduces to, (15),

$$t = \frac{\sin \theta}{\lambda N_0} \left( \frac{4\pi}{\sigma_s} \right)^{1/2}$$

### H. Reflection and Refraction

The index of refraction of a crystal for slow neutrons at angles and wave lengths which satisfy the Bragg condition is, (15),

$$n = 1 + \frac{2\pi N_0}{k^2} \sum_i \left[ \frac{(\sigma_s)_i}{4\pi} - k^2 \left( \frac{(\sigma_a)_i}{4\pi} \right)^2 \right]^{1/2}$$

and the extinction coefficient is

$$n_k = N_0 \sum_i \frac{(\sigma_a)_i}{2k}$$

$N_0$  = number of cells per unit volume of crystal.

$k$  = wave number.

$(\sigma_a)_i$  = absorption cross section for  $i^{\text{th}}$  atom.

$(\sigma_s)_i$  = scattering cross section for  $i^{\text{th}}$  atom.

The formulae also apply to disordered substances provided it is homogeneous over linear dimensions of the order of a wave length.  $N_0$  is then the number of molecules per unit volume and  $i$  is taken over the different kinds of atoms of the molecule.



Specular reflection of monochromatic neutrons by crystals occurs at grazing incidence (11) for which the reflectivity is given by, (15),

$$R = \left[ \frac{1 - \left(1 - \frac{2\mu}{\varphi^2}\right)^{1/2}}{1 + \left(1 + \frac{2\mu}{\varphi^2}\right)^{1/2}} \right]^2$$

$\varphi$  = angle of incidence from plane of reflection.

$$\mu = 1 - n$$

and the depth of penetration for grazing incidence is given by, (15),

$$t = \frac{\lambda}{2\pi\sqrt{2\mu}}$$

#### References

1. Hughes, Ph. Rev. 70, 219 (1946)
2. Arnold and Roberts, Phys. Rev. 70, 766 (1946)
3. Breit and Wigner, Phys. Rev. 49, 519 (1936)
4. Bethe, Rev. Mod. Phys. 9, 151 (1937)
5. Bethe and Placzek, Phys. Rev. 51, 450 (1937)
6. Peierls and Kapur, Proc. Roy. Soc. 166, 277 (1938)
7. Siegert, Phys. Rev. 56, 750 (1939)
8. Weisskopf and Ewing, Phys. Rev. 57, 472 (1940)
9. Fishback, Peaslee, and Weisskopf, Phys. Rev. 71, 145 (1947)
10. Bayley, Curtis Gaerttner, and Goudsmit, Phys. Rev. 50, 46 (1936)
11. Fermi, Recerca Scientifica, 7, Part 2, 13, (1936)
12. Fermi and Marschall, Phys. Rev. 71, 666, (1947)
13. Wick, Phys. Zeits. 38, 403 (1937)

14. Schwinger and Teller, Phys. Rev. 51, 775 (1937); Phys. Rev. 52, 286 (1937)
15. Goldberger and Seitz, Phys. Rev. 71, 294 (1947)
16. Wychoff. "The Structure of Crystals" - Chemical Catalogue Company, New York.



Table 9a. THERMAL NEUTRON ACTIVATION CROSS SECTIONS

The following table is a list of thermal neutron activation cross sections measured and reported by Seren, L., Friedlander, H. N., and Turkel, S. H., Phys. Rev. 72, 888 (1947). Activation cross sections were determined by measuring the absolute beta emission ( or positron and K-capture) from thin foils irradiated with thermal neutrons. Assuming one beta particle is emitted per neutron captured, the thermal neutron cross section,  $\sigma$ , was calculated from  $u = nv\sigma N$  where  $u$  = number of neutrons captured per unit time,  $nv$  = thermal neutron flux, and  $N$  = number of atoms of detector..

isotope Z sym. A	half life	isotopic cross section barns	natural atom cross section barns	prob. error per cent
8 O 18	31. s	$2.2 \times 10^{-4}$	$4. \times 10^{-7}$	20
9 F 19	12 s	0.0094	0.0094	20
11 Na 23	14.8 h	0.63	0.63	20
12 Mg 26	10.2 m	0.048	0.0054	20
13 Al 27	2.4 m	0.21	0.21	20
14 Si 30	170. m	0.116	0.00485	20
15 P 31	14.3 d	0.23	0.23	20
16 S 34	87.1 d	0.26	0.011	20
17 Cl 35	87.1 d	0.169	0.13	20
Cl 37	37. m	0.56	0.137	20
19 K 41	12.4 h	1.0	0.067	20
20 Ca 40	8.5 d	<0.000125	<0.00012	40
Ca 44	180. d	0.63	0.013	20
Ca 48	30. m	0.55	0.00105	20
Ca 48	150. m	0.025	0.00039	20

isotope Z sym. A			half life	isotopic cross section barns	natural atom cross section barns	prob. error percent
20	Ca	48	150. m	0.025	0.00039	20
21	Sc	45	85. d	22.	22.	20
22	Ti	50	6. m	0.141	0.0075	20
	Ti	50	72. d	0.039	0.0021	20
23	V	51	3.9 m	4.50	4.50	20
24	Cr	50	26.5 d	11.	0.50	40
	Cr	54	1.3 h	~0.0061	~0.00014	40
25	Mn	55	2.59 h	10.7	10.7	20
26	Fe	58	47. d	0.36	0.0010	20
27	Co	59	10.7 m	0.66	0.66	20
	Co	59	5.3 y	21.7	21.7	20
28	Ni	64	2.6 h	1.96	0.0173	20
29	Cu	63	12.8 h	2.82	2.0	20
	Cu	65	5. m	1.82	0.56	20
30	Zn	64	250. d	0.51	0.26	20
	Zn	68	57. m	1.09	0.19	20
	Zn	68	13.8 h	0.31	0.054	20
31	Ga	69	20. m	1.40	0.855	20
	Ga	71	14.1 h	3.36	1.30	20
32	Ge	70	40. h	0.073	0.0155	20
	Ge	70	11. d	~0.45	~0.095	40
	Ge	74	89. m	0.38	0.14	20
	Ge	76	12. h	0.085	0.0055	20



isotope Z sym. A			half life	isotopic cross section barns	natural atom cross section barns	prob. error percent
33	As	75	26.8 h	4.2	4.2	20
34	Se	74	115. d	22.	0.2	40
	Se	78,80	19. m		0.23	20
	Se	78,80	57. m		0.017	20
	Se	82	30. m	0.060	0.0056	20
35	Br	79	18. m	8.1	4.1	20
	Br	79	4.4 h	2.76	1.39	20
	Br	81	34. h	2.25	1.11	20
37	Rb	85	19.5 d	0.72	0.52	20
	Rb	87	17.5 m	0.122	0.033	20
38	Sr	86	2.7 h	1.29	0.127	20
	Sr	88	55. d	0.0050	0.00415	20
39	Y	89	60. h	1.24	1.24	20
40	Zr	92	63. d	0.33	0.073	40
	Zr	94	17.0 h	0.053	0.009	20
	Zr	96	6. m	~1.07	~0.016	40
41	Cb	93	6.6 m	~1.0	~1.0	40
42	Mo	100	19. m	0.475	0.044	20
	Mo	98	67. h	0.415	0.10	20
	Mo	92?	7. h		<0.001	40
44	Ru	102,104	4. h		0.122	20
	Ru	?	37. h		0.15	20

isotope Z sym. A			half life	isotopic cross section barns	natural atom cross section barns	prob. error percent
44	Ru	?	40. d		0.37	20
45	Rh	103	44. s	137.	137.	10
	Rh	103	4.2 m	11.6	11.6	10
46	Pd	108	13. h	11.2	3.0	20
	Pd	110	26. m	0.39	0.0525	20
47	Ag	107	2.3 m	44.3	23.	20
	Ag	109	22. s	97.	46.6	20
	Ag	109	225. d	2.3	1.1	20
48	Cd	114	2.5 d	1.1	0.30	20
	Cd	114	43. d	0.14	0.040	20
	Cd	116	3.75 h	1.4	0.10	20
	Cd	?	2. m		0.05	20
49	In	113	48. d	56.	2.52	10
	In	115	13. s	51.8	49.5	10
	In	115	54. m	144.6	138.	10
50	Sn	112	105. d	~1.1	~0.012	40
	Sn	124	9. m	0.574	0.039	20
	Sn	<125	40. m		0.0142	20
	Sn	<125	26. h		0.072	20
	Sn	<125	10. d		0.009	20
	Sn	<125	400. d		0.018	20
51	Sb	121	2.8 d	6.8	3.8	20
	Sb	123	60. d	2.5	1.1	20



isotope Z sym. A			half life	isotopic cross section barns	natural atom cross section barns	prob. error percent
52	Te	126	9.3 h	0.78	0.15	20
	Te	126	90. d	0.073	0.014	20
	Te	128	72. m	0.133	0.0436	20
	Te	128	32. d	0.0154	0.00504	20
	Te	130	25. m	0.222	0.0735	20
	Te	130	30. h	<0.008	<0.003	40
53	I	127	25. m	6.25	6.25	20
55	Cs	133	3. h	0.016	0.016	20
	Cs	133	1.7 y	25.6	25.6	20
56	Ba	138	86. m	0.511	0.367	20
57	La	139	40. h	8.4	8.4	20
59	Pr	141	19.3 h	10.1	10.1	20
62	Sm	?	21. m		1.10	20
	Sm	152	46. h	138.	35.8	20
	Sm	?	60. d		<0.008	40
63	Eu	151	9.2 h	1380.	681.	20
	Eu	151,152	5-8 y		390.	20
64	Gd	?	9.5 h		2.3	20
	Gd	?	20. h		~0.9	40
	Gd	?	8.6 d		~0.6	40
	Gd	?	160. d		<0.25	40

isotope Z sym. A			half life	isotopic cross section barns	natural atom cross section barns	prob. error percent
65	Tb	159	3.9 h	10.7	10.7	20
66	Dy	164	140. m	2620.	725.	10
	Dy	164	1.25 m	120.	33.	40
67	Ho	165	30. h	59.6	59.6	20
69	Tm	169	105. d	106.	106.	20
71	Lu	175,176	3.4 h		15.9	20
	Lu	176	6.6 d	3640.	91.0	20
72	Hf	180	46. d	10.0	3.5	20
73	Ta	?	16.2 m		0.034	20
	Ta	181	117. d	20.6	20.6	20
74	W	184	77. d	2.12	0.64	20
	W	186	24.1 h	34.2	10.2	20
75	Re	185	90. h	101.	38.5	20
	Re	187	18. h	75.3	46.5	20
76	Os	190	30. h	2.50	0.66	20
	Os	192	17. d	5.34	2.19	20
77	Ir	191	1.5 m	260.	100.	40
	Ir	191	70. d	1000.	388.	20
	Ir	193	20.7 h	128.	79.0	20
78	Pt	196	18. h	1.1	0.30	20



isotope Z sym. A			half life	isotopic cross section barns	natural atom cross section barns	prob. error percent
78	Pt	196	3.3 d	4.5	1.20	20
	Pt	198	31. m	3.92	0.292	20
79	Au	197	2.7 d	96.4	96.4	10
80	Hg	204	5.5 m	0.34	0.0228	20
	Hg	202,204	51.5 d		0.725	20
81	Tl	203	4.23 m	0.273	0.079	20
	Tl	205	3.5 y	3.1	2.2	20
83	Bi	209	5.0 d	0.015	0.015	20

## 10. NEUTRON DIFFUSION

### A. Diffusion Equation

The absence of charge associated with neutrons leads to a behavior in matter entirely different from that of charged particles. Energy is lost wholly by elastic collisions with the absorbing or scattering nuclei. Neutrons introduced into a block of matter, therefore, perform repeated collisions, altering their energies and directions until some equilibrium configuration in both space and energy is established. Ultimately, they are lost either by capture to form compound nuclei, decay into a proton and electron with a half-life of approximately twenty minutes, or by diffusion out of the region. If the diffusing medium is hydrogenous, i.e., consists mainly of protons, the conditions for diffusion are the most favorable. The elastic scattering cross section is large compared to the capture cross section, and the large energy and momentum transfer rapidly reduces neutrons to thermal energies. The diffusion of neutrons in such moderators resembles in most respects, the self-diffusion of gases. Substances containing heavy nuclei, on the other hand, allow small or negligible energy and momentum transfer; the neutron scatters elastically as from a solid and relatively immovable object. The conditions here are more like the diffusion of an electron gas.

The equilibrium spacial and energy distribution of neutrons in a moderator depends upon the geometries of the moderator, the neutron source (or sources), and absorbing or reflecting substance, and upon the capture cross section curve of any absorbers present, and finally, on the mean temperature of the moderator. The distributions in many simple geometrical forms of moderators can be found from solutions of the neutron diffusion equation with appropriate boundary conditions. Satisfactory moderator substances include only the lightest elements. Of these, usually only graphite and hydrogenous materials



such as paraffin and water (including deuterium) are commonly used. Most of the other light elements are unsatisfactory because they possess resonance capture cross sections which are considerably greater than their scattering cross sections. The diffusion equation is an expression of the law of conservation for neutrons. The time rate of change in the number of neutrons,  $n$ , per cc at a point  $(x,y,z)$  and at time,  $t$ , equals the thermal neutron flux plus the number of thermal neutrons produced per cc minus the number of thermal neutrons absorbed per cc.

$$\frac{dn}{dt} = D\nabla^2 n + q - \frac{n}{\tau}$$

For steady state diffusion  $dn/dt = 0$  and only thermal neutrons in equilibrium at temperature  $T$  are considered. The terms in the equations are then

$D = 1/3\lambda v_0$  = diffusion coefficient.

$\lambda = 1/N\sigma$  = thermal neutron mean free path,

$v_0 = \frac{(8kT)^{1/2}}{\pi m}$  = average velocity, assuming a Maxwellian distribution.

$N$  = number of nuclei per cc.

$\sigma$  = capture cross section.

$q$  = source strength; number of neutrons produced per cc as a function of position.

$\tau$  = mean life of thermal neutrons before capture.

Several additional quantities are useful for diffusion calculations.

Neutron current,  $S$ , is the number of neutrons per unit time crossing a unit area normal to the gradient of the neutron density

$$S = -D\nabla n$$

Diffusion length,  $L$ , is the mean distance a neutron travels before capture:

$$L = D\tau = \frac{\lambda}{3N\sigma}$$

It is defined by the expression  $P = \exp(-X/L)$  where  $P$  is the probability a neutron will travel a distance  $X$  before capture. For thermal neutrons in light elements,  $L$  is of the order of several cm.

### B. Point Source in Infinite Medium (1,2)

The neutron density is spherically symmetric and  $q = 0$  for  $r \neq 0$ . The density at radial distance  $r$ , for a source of strength  $Q$  is

$$n = \frac{3Q}{4\pi^2\lambda} e^{-r/L}$$

### C. Plane Source in Infinite Medium (1,2)

$q = 0$  except in the plane  $Z = 0$  where the source strength is  $Q$  neutrons per unit time per unit area.

$$n = \frac{3LQ}{2\lambda} e^{-Z/L}$$

### D. Point Source in Long Column (2)

For an infinitely long rectangular column of cross sectional width  $a$  and coaxial to the  $Z$  axis, with a point source of strength  $Q$  represented by Dirac's  $\delta$  function at  $(0,0,0)$ , the neutron density at any point in the medium is

$$n = Q \sum_n \sum_m \frac{6b_{mn}}{\lambda a^2 v_0} \cos \frac{n\pi x}{a} \cos \frac{m\pi y}{a} e^{-Z/b_{mn}}$$

### E. Finite Source in Infinite Medium (2)

For a source which is a function of the vector position  $\mathbf{r}'$ , the neutron density at any vector position  $\mathbf{r}$  is given by the volume integral over the source



$$n(\underline{r}) = \int \frac{3q(\underline{r}')}{4\pi\lambda v_0 |\underline{r} - \underline{r}'|} e^{-|\underline{r} - \underline{r}'|} dv'$$

At great distances compared to the largest dimension of the source, the density is equivalent to a point source.

#### F. Point Source in Finite Sphere (2)

For a point source of strength  $Q$  placed at the center of a sphere of radius  $R$ , the neutron density is spherically symmetric and at any radius,  $r$ , is given by

$$n = \frac{Q}{\pi D r} \frac{e^{-R/L}}{e^{2R/L} - 1} \sinh \frac{R - r}{L}$$

#### G. Semi-Infinite Medium with Plane Boundary (2)

If a semi-infinite non-absorbing medium is bounded by a vacuum at the  $Y-Z$  plane and the neutron source is either a plane or an arbitrary form embedded in the medium at a great distance from the surface, the neutron density in the medium is

$$n = Ax + B$$

From the boundary conditions

$$nv = a(1 + \frac{x}{L})$$

where  $L$  is the extrapolated distance from the boundary to where the straight line representing the neutron density intercepts the  $x$  axis ( $n = 0$ ).  $L$  is

the extrapolated end point and is given approximately by

$$L = \frac{2D}{v} = \frac{2}{3} \lambda$$

An exact solution leads to a value of  $L = 0.7104$  and to a depression in the neutron density with a distance from the boundary of the order of inside the medium. At the boundary, the fractional depression below the straight line variation in density is

$$\frac{n'}{n} = \frac{1}{0.7104\sqrt{3}}$$

#### H. Absorbing Foil in Infinite Medium with Point Source (2)

Assuming the absorbing foil to be a spherical shell of radius  $r_0$  and thickness  $t$  surrounding a point source in an infinite medium, the fractional depression in the neutron density at the foil

$$f = \frac{3N\sigma_a t L r_0}{3N\sigma_a t r_0 L + L\lambda + r_0\lambda}$$

$\sigma_a$  = absorption cross section of foil.

The flux of neutrons from the surface of the medium varies as

$$\cos \theta + \frac{3}{2} \cos^2 \theta$$

#### I. Production of Thermal Neutrons

Neutrons are always produced with energies very much greater than the thermal region. The purpose of a moderator is to slow down fast neutrons until they reach equilibrium energies of the order of  $kT$ . In the diffusion



equation the quantity  $q$  is defined as the number of thermal neutrons produced per cc per second without regard to how thermal neutrons were produced. Solutions of the equation can readily be found when the source of thermal neutrons assumes the simplest geometrical form. Actually, however, fast neutrons having a source producing  $Q$  neutrons per second must first be slowed down by elastic collisions until they enter the energy region corresponding to thermal velocities. The source of thermal neutrons will, therefore, be represented by some intensity distribution in space about the true source of fast neutrons. For this purpose,  $q$  is defined explicitly as the number of neutrons reaching energy  $E$  per cc per second.

The ratio of the neutron energy after collisions to the energy before collision is, on the average, a constant whose magnitude depends on the mass of the scattering nuclei.

$$\frac{E_1}{E_2} = e^{\xi}$$

$$\begin{aligned}\xi &= 1 - \frac{(M-1)^2}{2M} \log \frac{M+1}{M-1} \\ &\approx \frac{2}{M+1} \quad (\text{for heavy nuclei})\end{aligned}$$

$E_1$  = initial energy.

$E_2$  = final energy.

$M$  = mass of nucleus.

The average total number of collisions required to reduce a neutron from energy  $E_0$  to  $E$  is then

$$N = \frac{1}{\xi} \log \frac{(E_0)}{E}$$

By this process, the quantity  $q$  can be calculated from solutions of Fermi's age equation with appropriate boundary conditions.

$$\nabla^2 q = \frac{S q}{\delta \tau}$$

$$d\tau = \frac{\lambda^2}{3\xi} d(\log E) \text{ cm}^2$$

$$\tau = \int_E^{E_0} \frac{\lambda^2}{3\xi} d(\log E) \quad (\text{Fermi's "Age"})$$

#### J. Point Source of Fast Neutrons

If a point source located in an extended medium produces fast neutrons of homogeneous energy  $E_0$ , the number of neutrons slowed to thermal energy is represented by the Gauss distribution about the source:

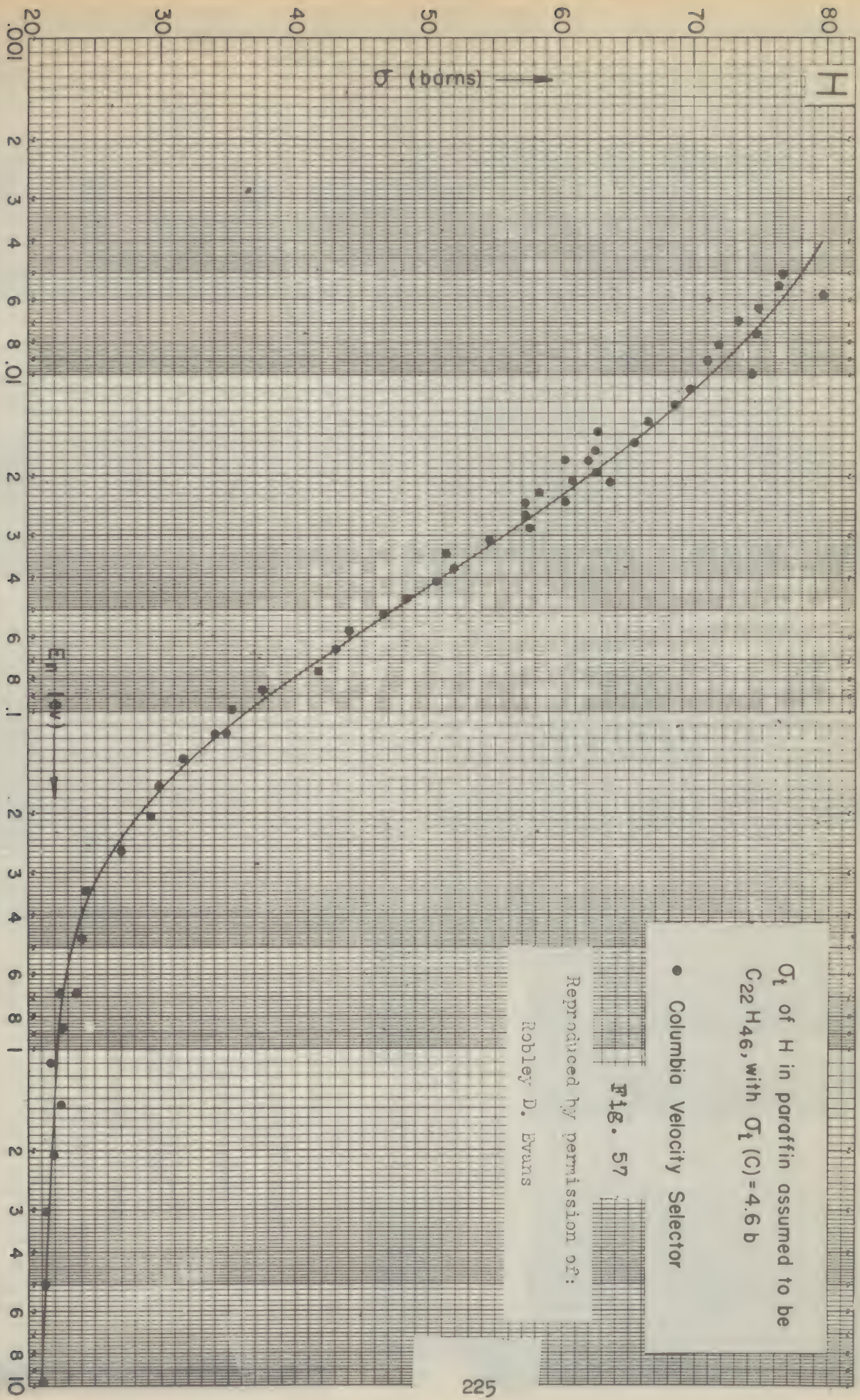
$$q = \frac{Q_0 e^{-r^2/4\tau}}{(4\pi\tau)^{3/2}}$$

At a distance  $r = 2\sqrt{\tau}$  from the source,  $q$  has been reduced by  $1/e$ .

#### References

1. Bethe, H., Rev. Mod. Phys. 9, 131 (1947)
2. Christy, R. F., L. A. Report No. 24.





$\sigma_1$  of H in paraffin assumed to be  $C_{22}H_{46}$ , with  $\sigma_1(C) = 4.6$  b

• Columbia Velocity Selector

Fig. 57

Reproduced by permission of:

Robley D. Evans



$\sigma_s$ :

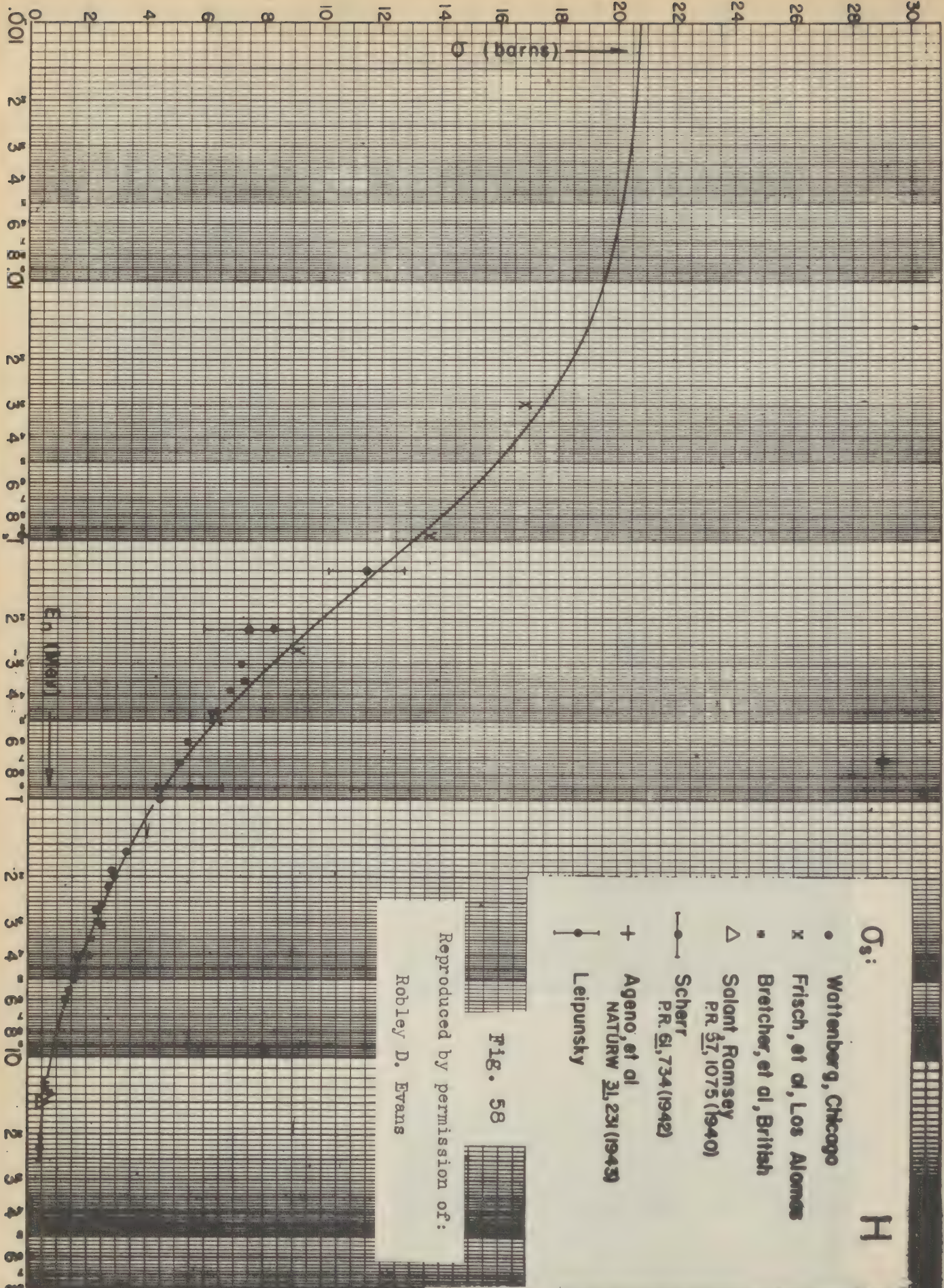
H

- Wattenberg, Chicago
- x Frisch, et al, Los Alamos
- Brecher, et al, British
- △ Solant Ramsey  
PR. 57, 1075 (1940)
- Scherr  
PR. 61, 734 (1942)
- + Ageno, et al  
NATURW. 31, 231 (1943)
- Leipunsky

Fig. 58

Reproduced by permission of:

Robley D. Evans





Reproduced by permission of:

Robley D. Evans

$\sigma_t^D$

• Los Alamos

x Zinn, et al  
PR. 56,260 (1939)

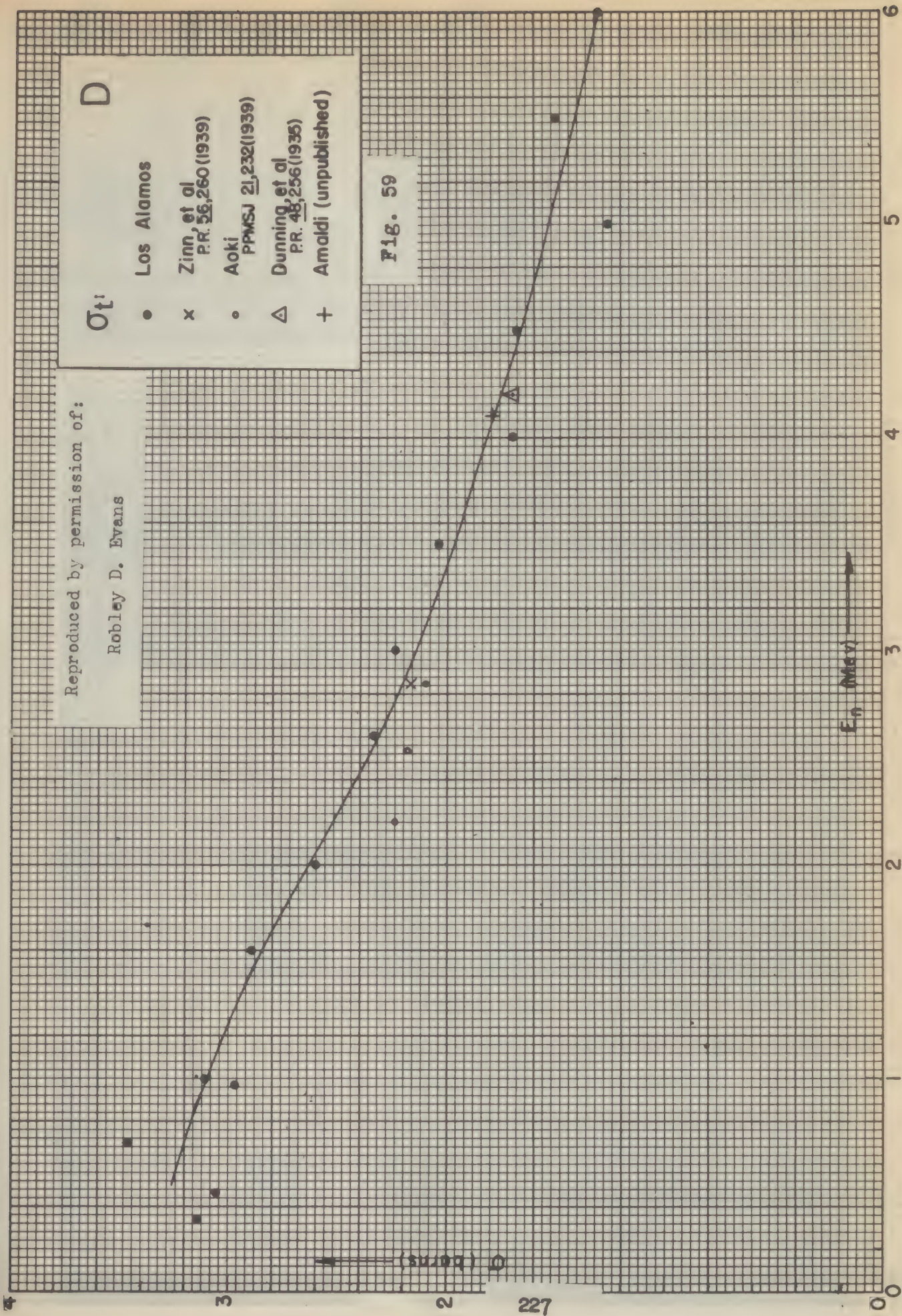
• Aoki  
PPWSJ 21,232 (1939)

$\Delta$  Dunning, et al  
PR. 48,256 (1935)

+ Amaldi (unpublished)

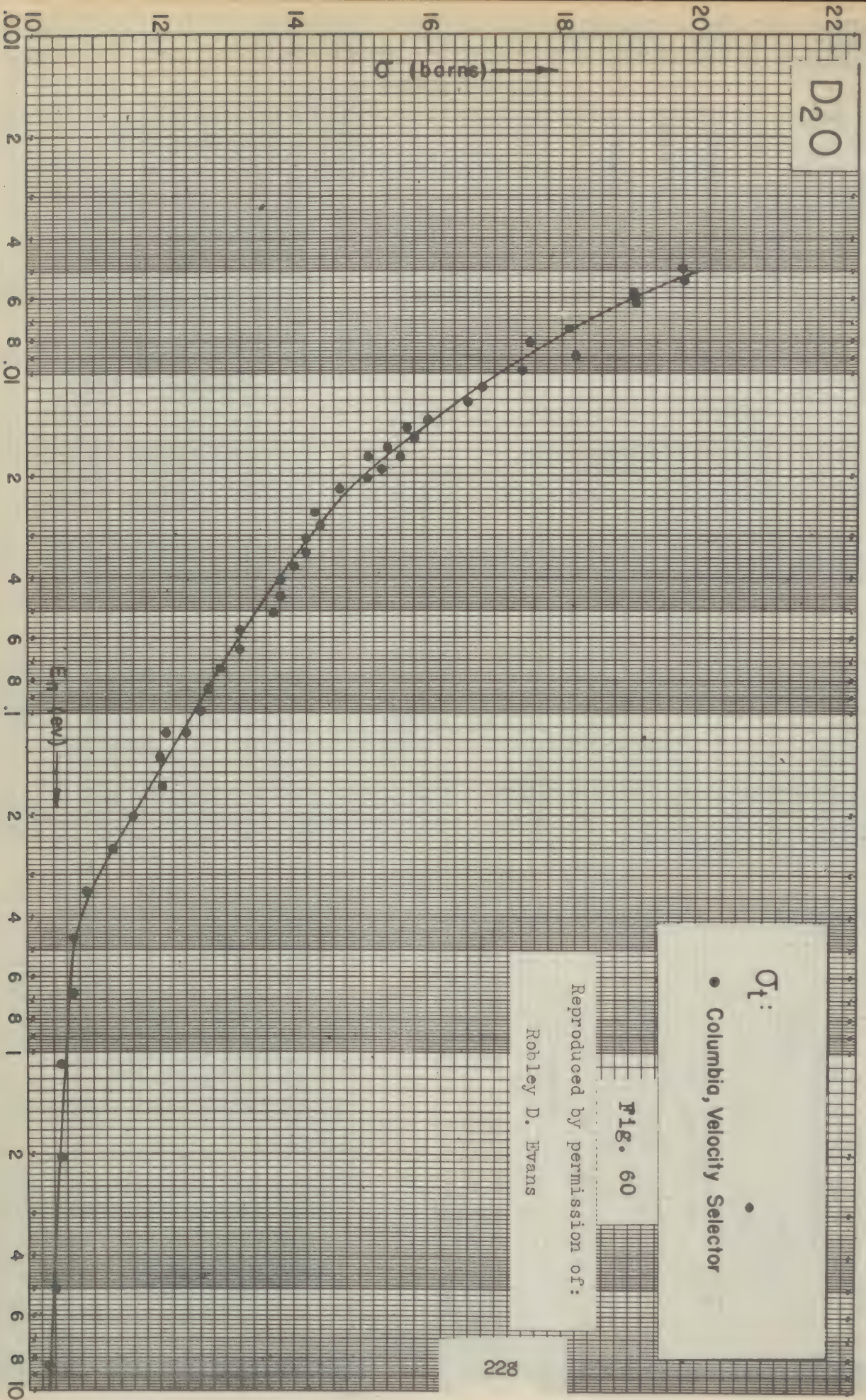
Fig. 59

$E_n$  (MeV)





D<sub>2</sub>O



$\sigma_t$ :

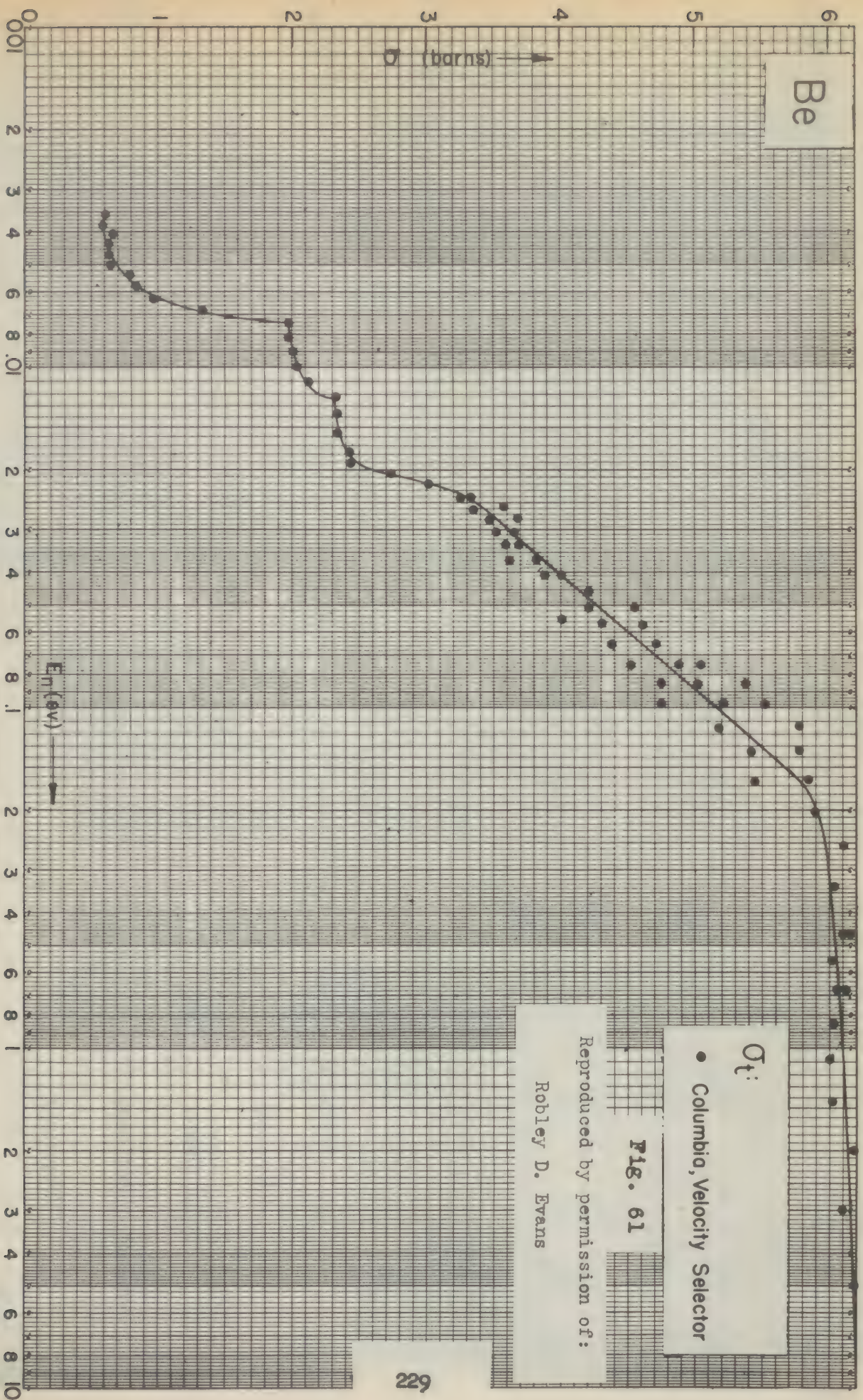
• Columbia, Velocity Selector

Fig. 60

Reproduced by permission of:

Robley D. Evans







Be

O†:

Reproduced by permission of:  
 Robley D. Evans

• Wattenberg

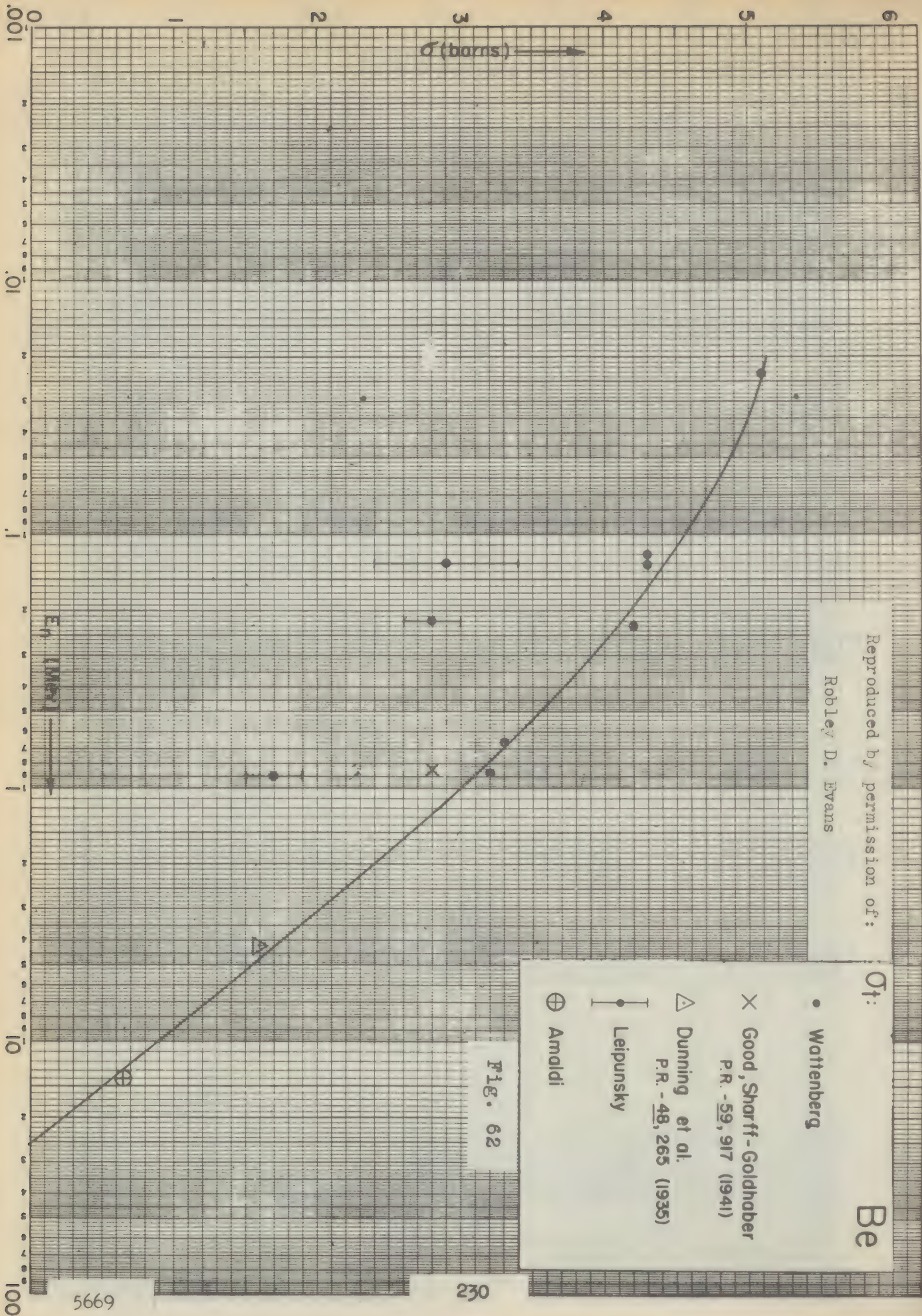
× Good, Sharff-Goldhaber  
 P.R. - 59, 917 (1941)

△ Dunning et al.  
 P.R. - 48, 265 (1935)

• Leipunsky

⊕ Amaldi

Fig. 62





Reproduced by permission of:

Robley D. Evans

$\sigma_a$ :

• Los Alamos, Velocity  
Selector

value of  $\sigma_a$  V:

barns meter/ $\mu$  sec barns  $\sqrt{eV}$   
161 116

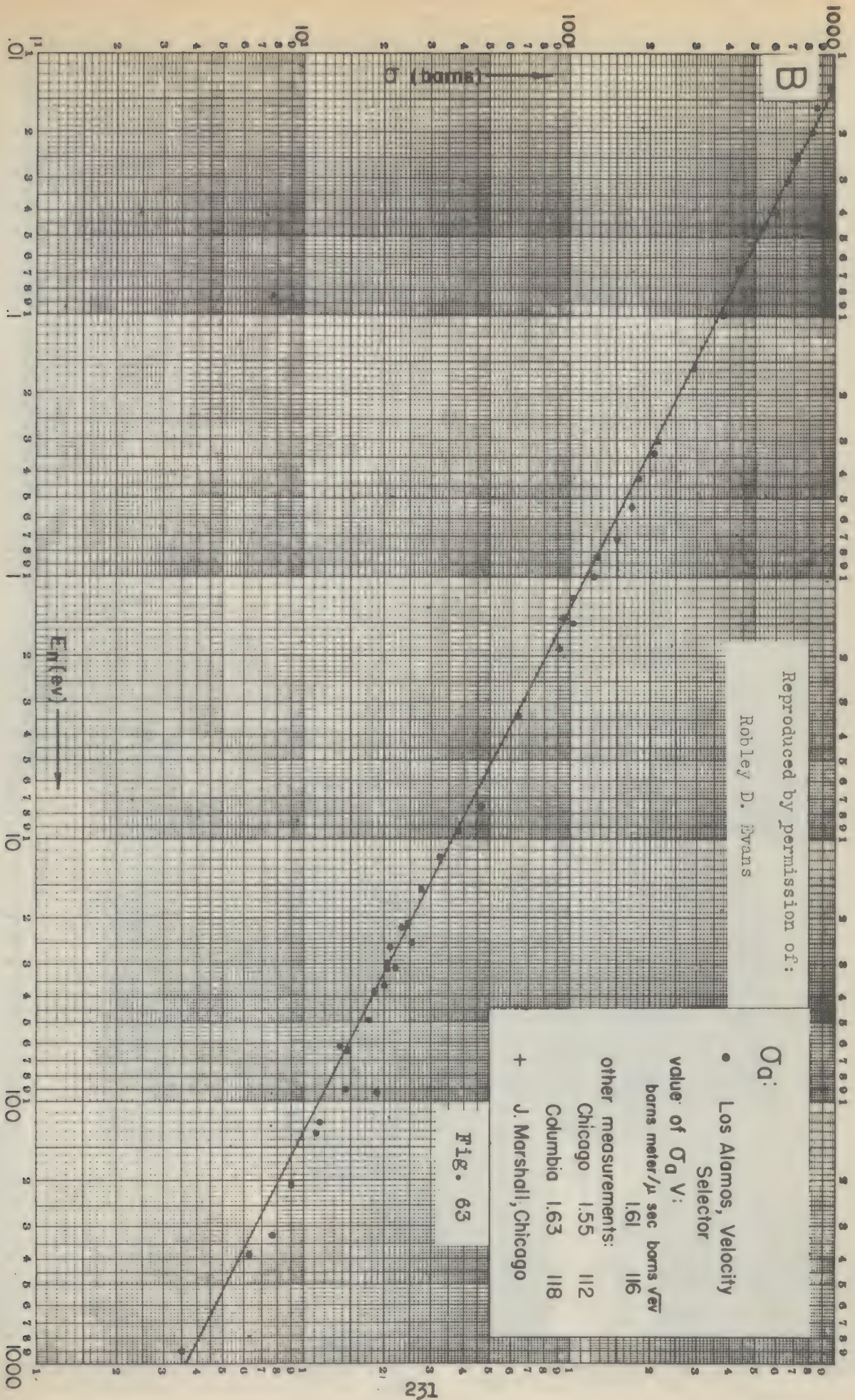
other measurements:

Chicago 1.55 112

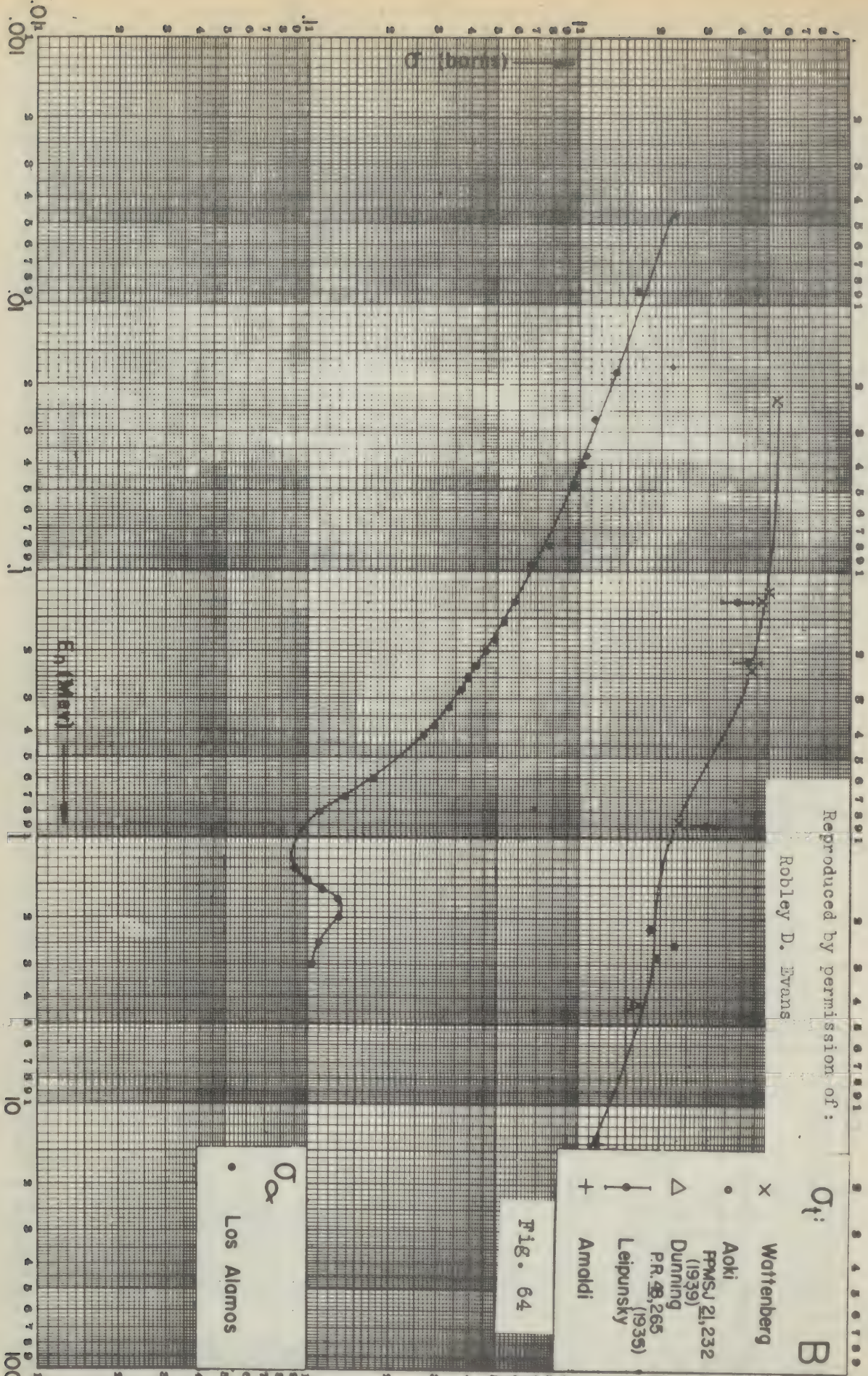
Columbia 1.63 118

+ J. Marshall, Chicago

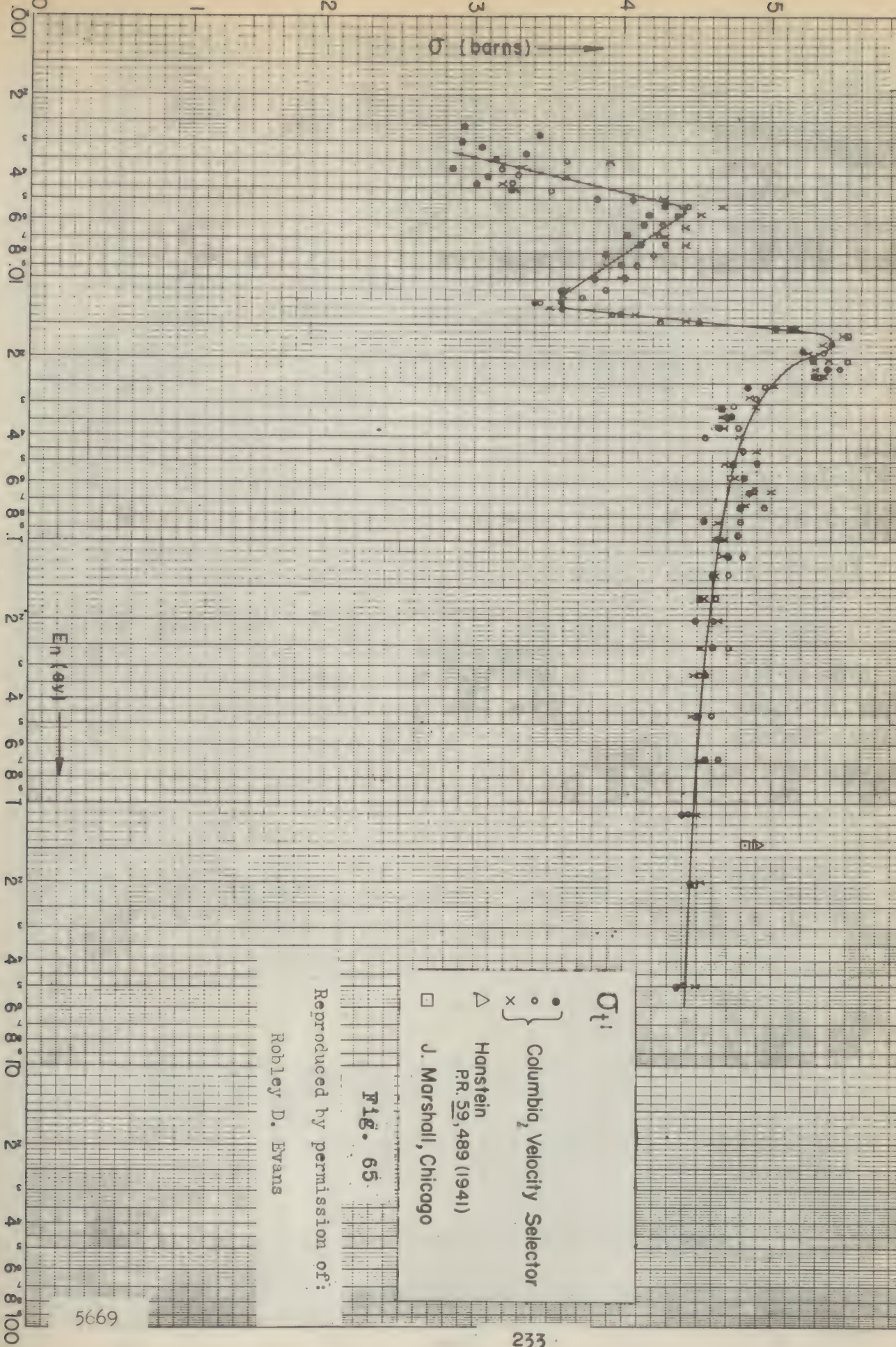
Fig. 63











$\sigma_d$

$\left. \begin{array}{c} \bullet \\ \times \end{array} \right\}$  Columbia, Velocity Selector

$\Delta$  Honstein  
P.R. 59,489 (1941)

$\square$  J. Marshall, Chicago

Fig. 65

Reproduced by permission of:

Robley D. Evans



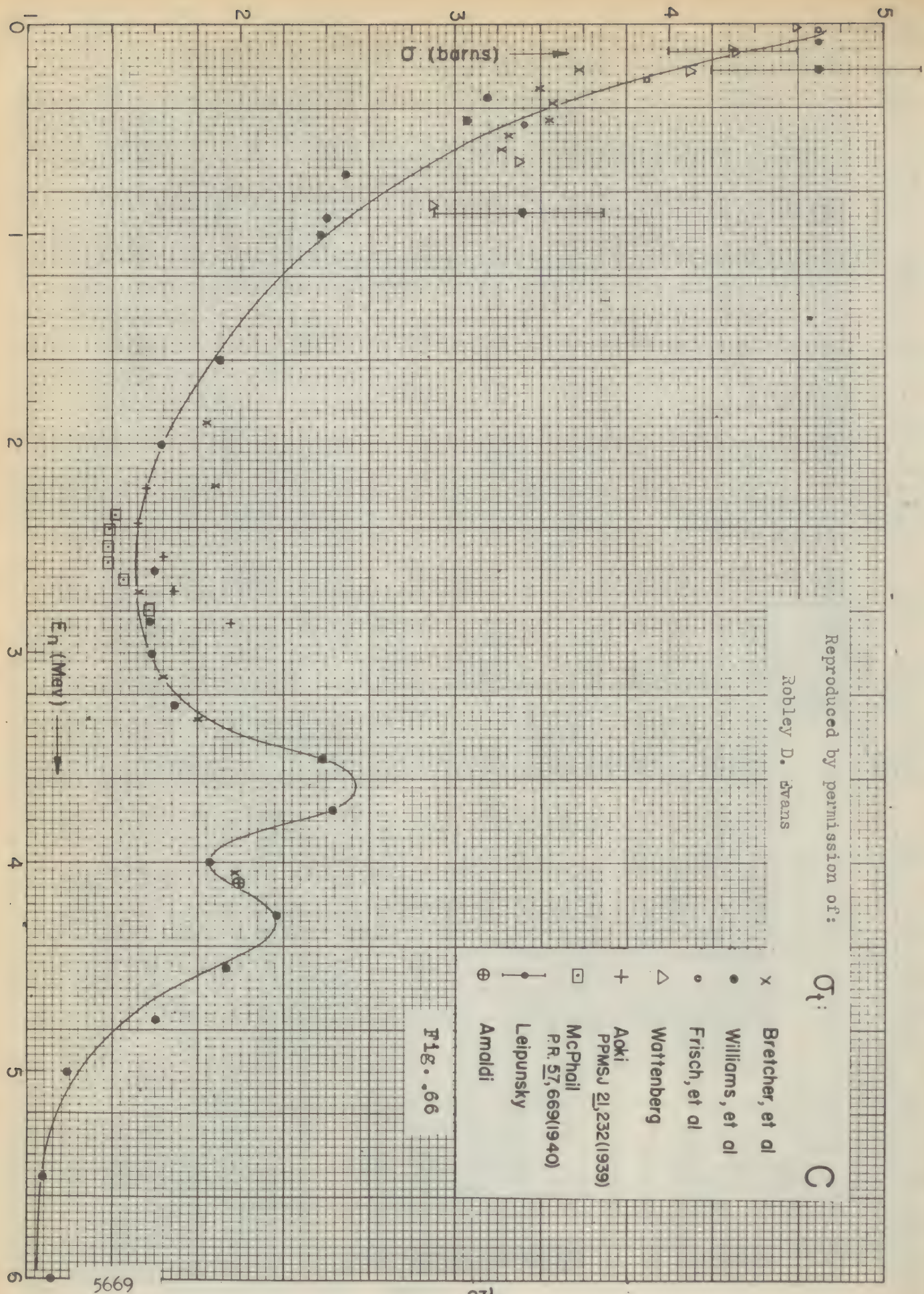
Reproduced by permission of:

Robley D. Evans

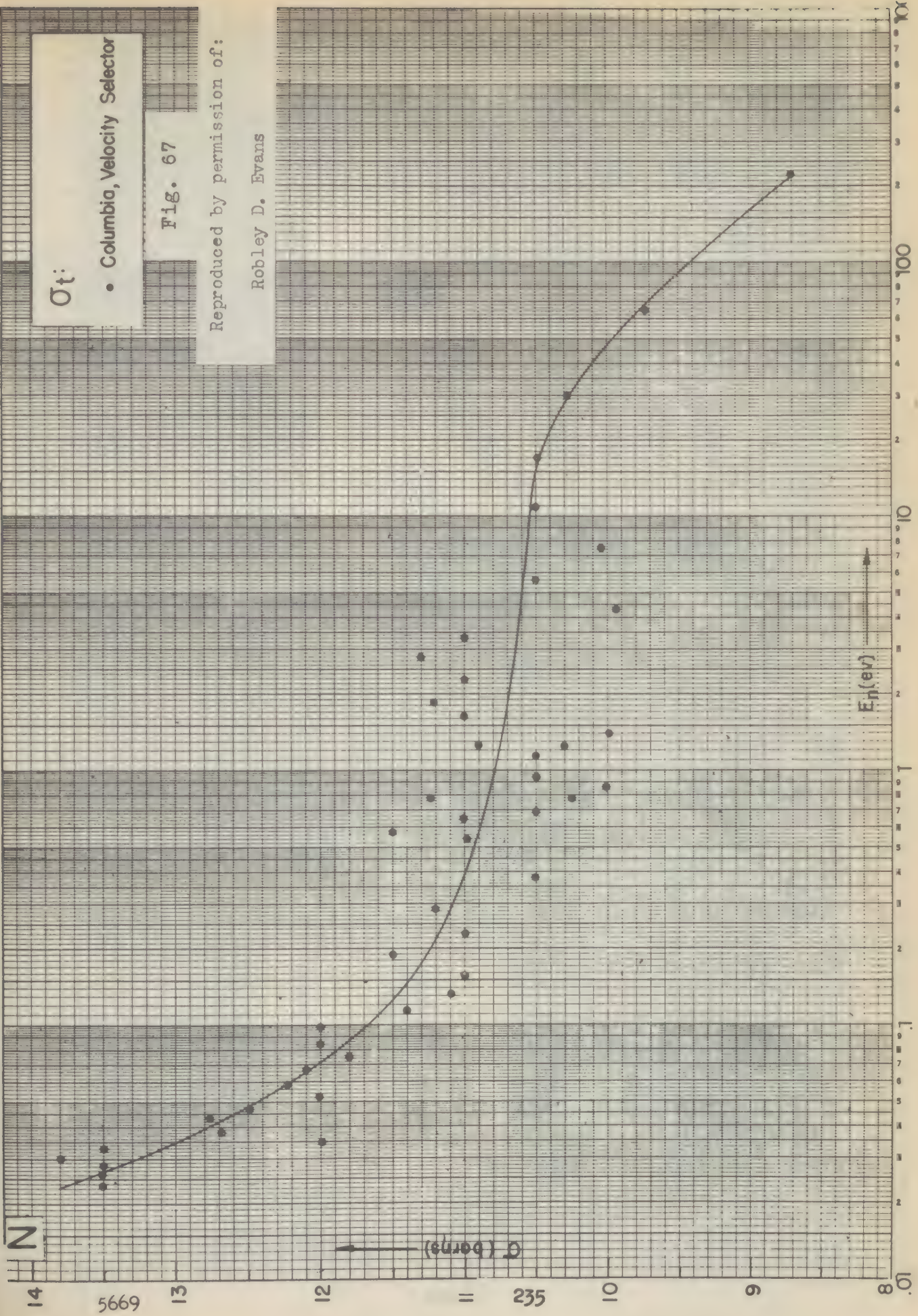
$\sigma_t$ : C

- x Brecher, et al
- Williams, et al
- Frisch, et al
- △ Wattenberg
- + Aoki  
PPMSJ 21,232 (1939)
- ◻ McPhail  
P.R. 57,669 (1940)
- Leipunsky
- ⊕ Amaldi

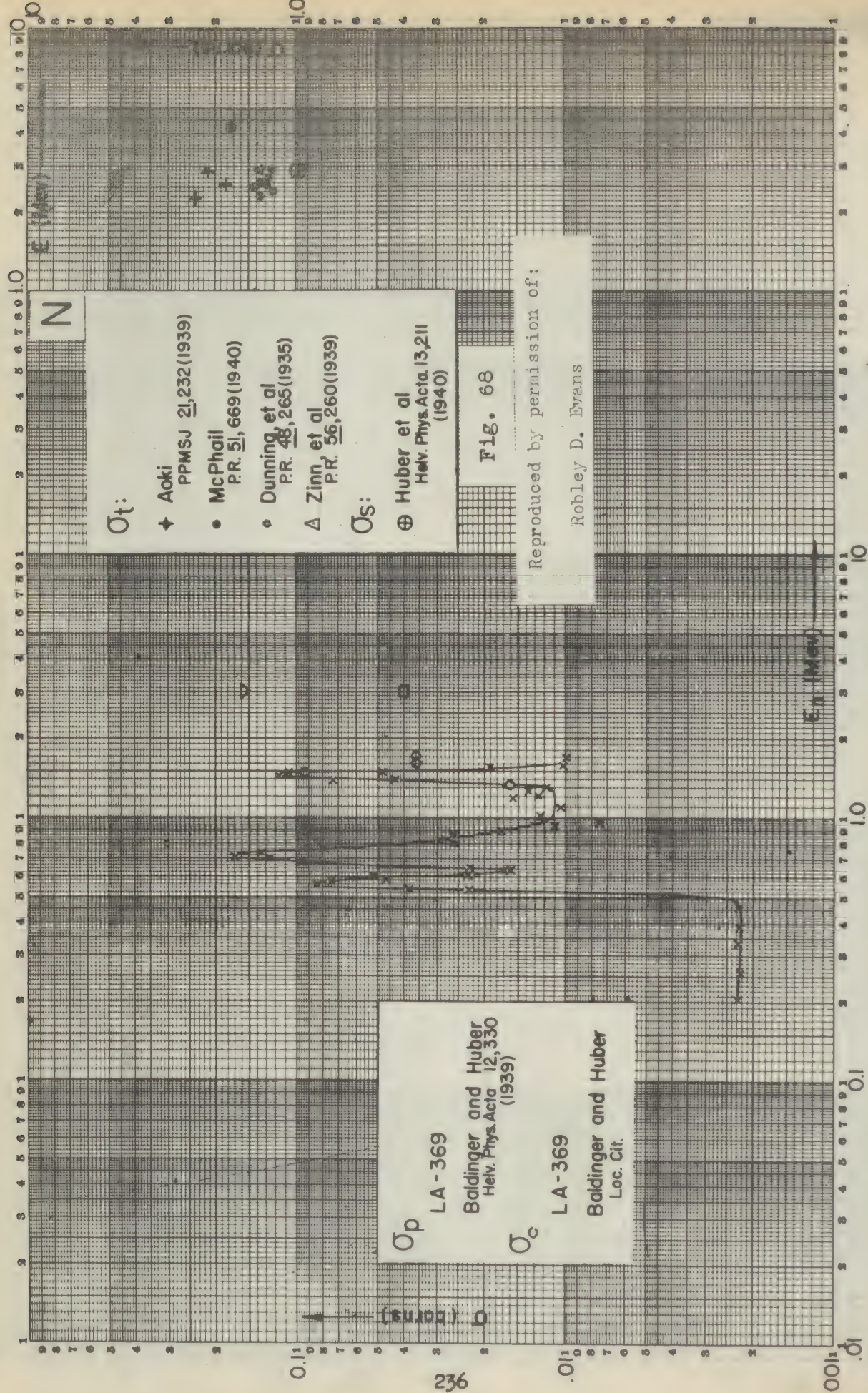
Fig. .66













$\sigma_t$ 

● Columbia

x Hanstein;

PR. 59,489 (1941)

Fig. 69

Reproduced by permission of:

Robley D. Evans

 $\sigma$  (barns) $E_n$  (ev)

2

1

0

0.1

0.2

0.4

0.6

0.8

1.0

1.2

1.4

1.6

1.8

2.0

2.2

2.4

2.6

2.8

3.0

3.2

3.4

3.6

3.8

4.0

4.2

4.4

4.6

4.8

5.0

5.2

5.4

5.6

5.8

6.0

6.2

6.4

6.6

6.8

7.0

7.2

7.4

7.6

7.8

8.0

8.2

8.4

8.6

8.8

9.0

9.2

9.4

9.6

9.8

10.0



Reproduced by permission of:

Robley D. Evans

Al

Ot

Wattenberg

Aoki

PPMSJ 21,232 (1939)

Good, Sharff - Goldhaber  
P.R. 59, 917 (1941)

McPhail  
P.R. 57, 669 (1940)

Dunning et al  
P.R. 48, 265 (1935)

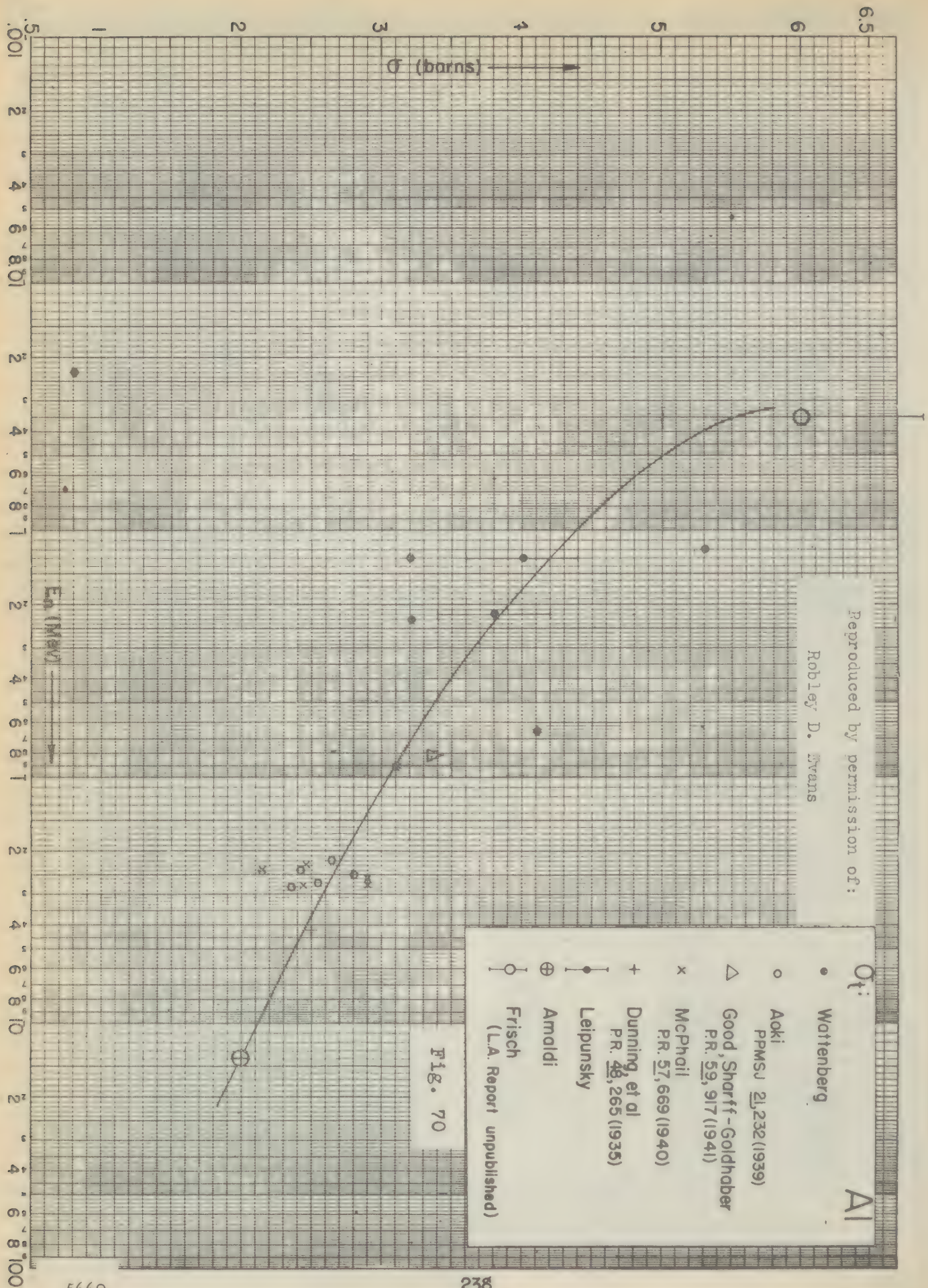
Leipunsky

Amaldi

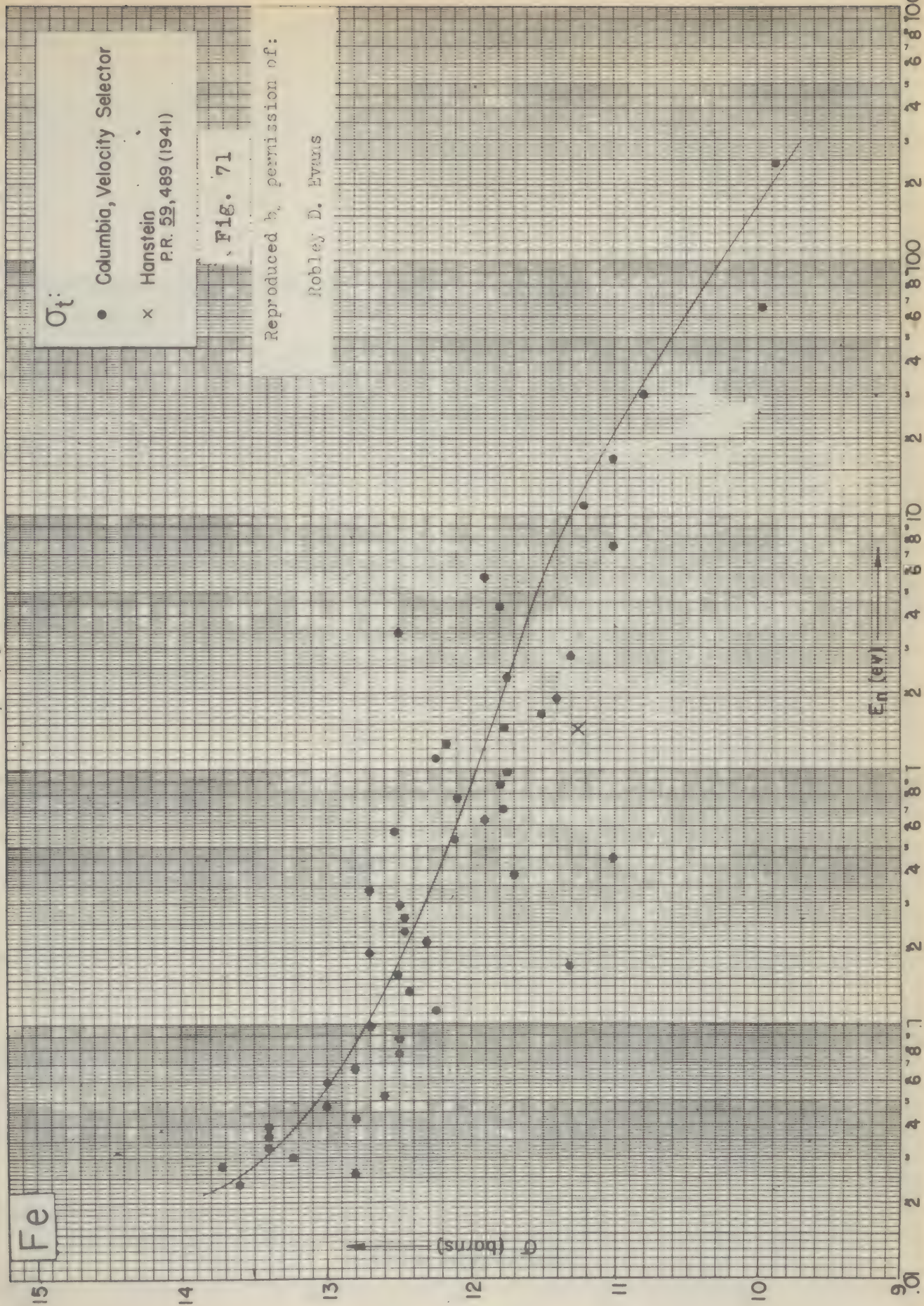
Frisch

(L.A. Report unpublished)

Fig. 70









Reproduced by permission of:

Robley D. Evans

Fe

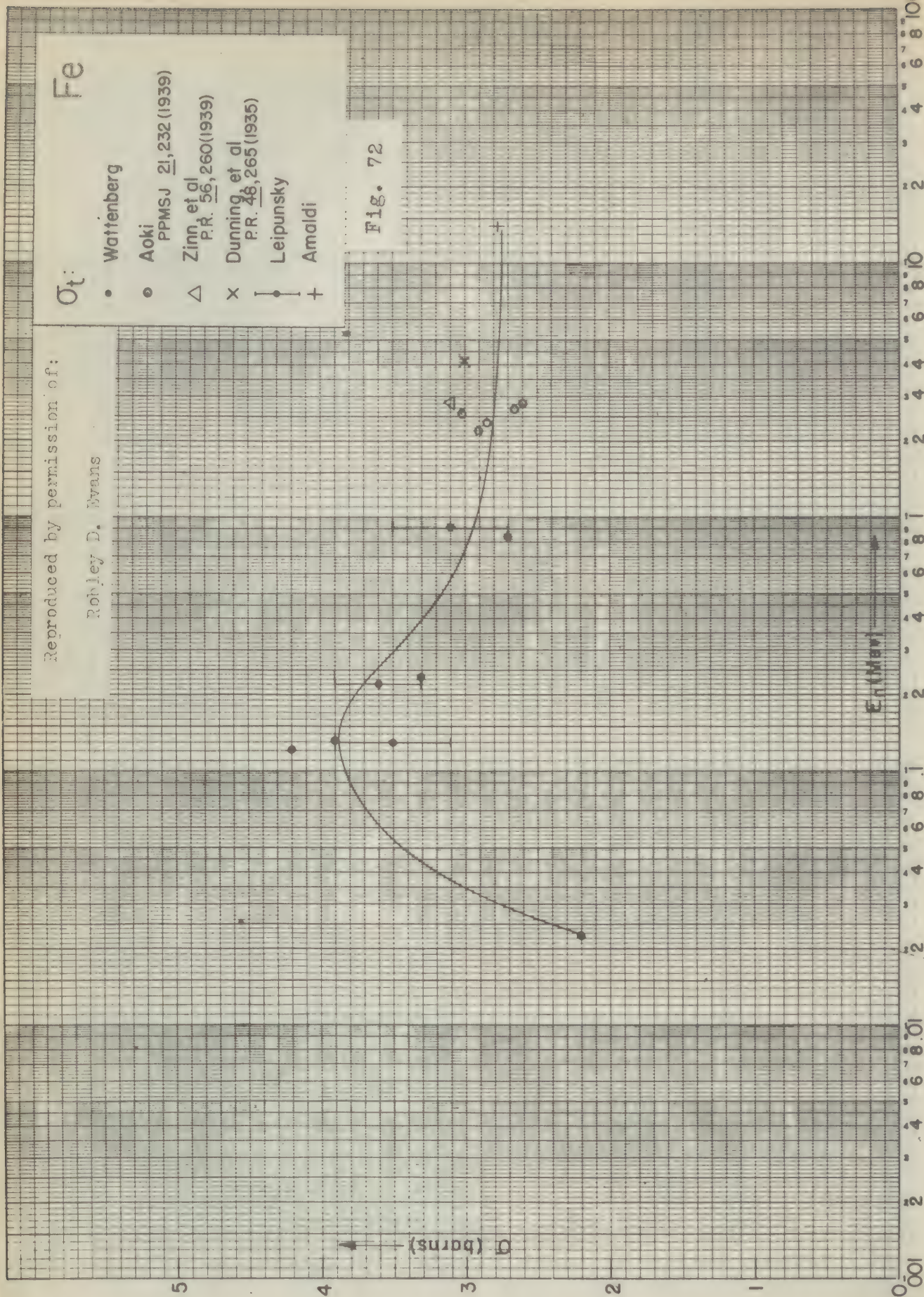
 $\sigma_t$ :

- Wattenberg
- Aoki  
PPMSJ 21, 232 (1939)
- $\Delta$  Zinn et al  
P.R. 56, 260 (1939)
- $\times$  Dunning et al  
P.R. 46, 265 (1935)
- $\vdash$  Leipunsky
- $+$  Amaldi

Fig. 72

(barns)  $\sigma$  $E_\gamma$  (MeV)

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100

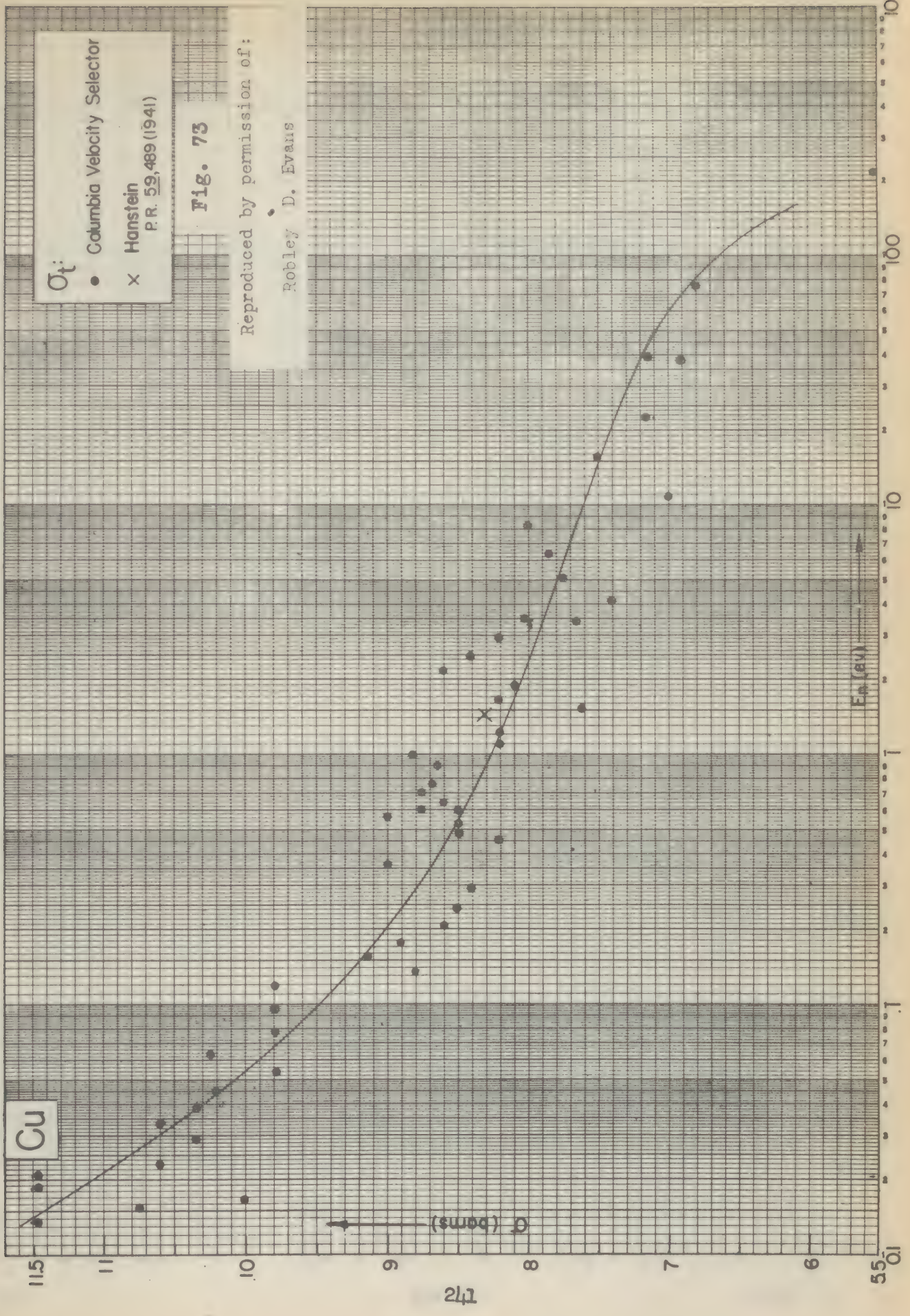




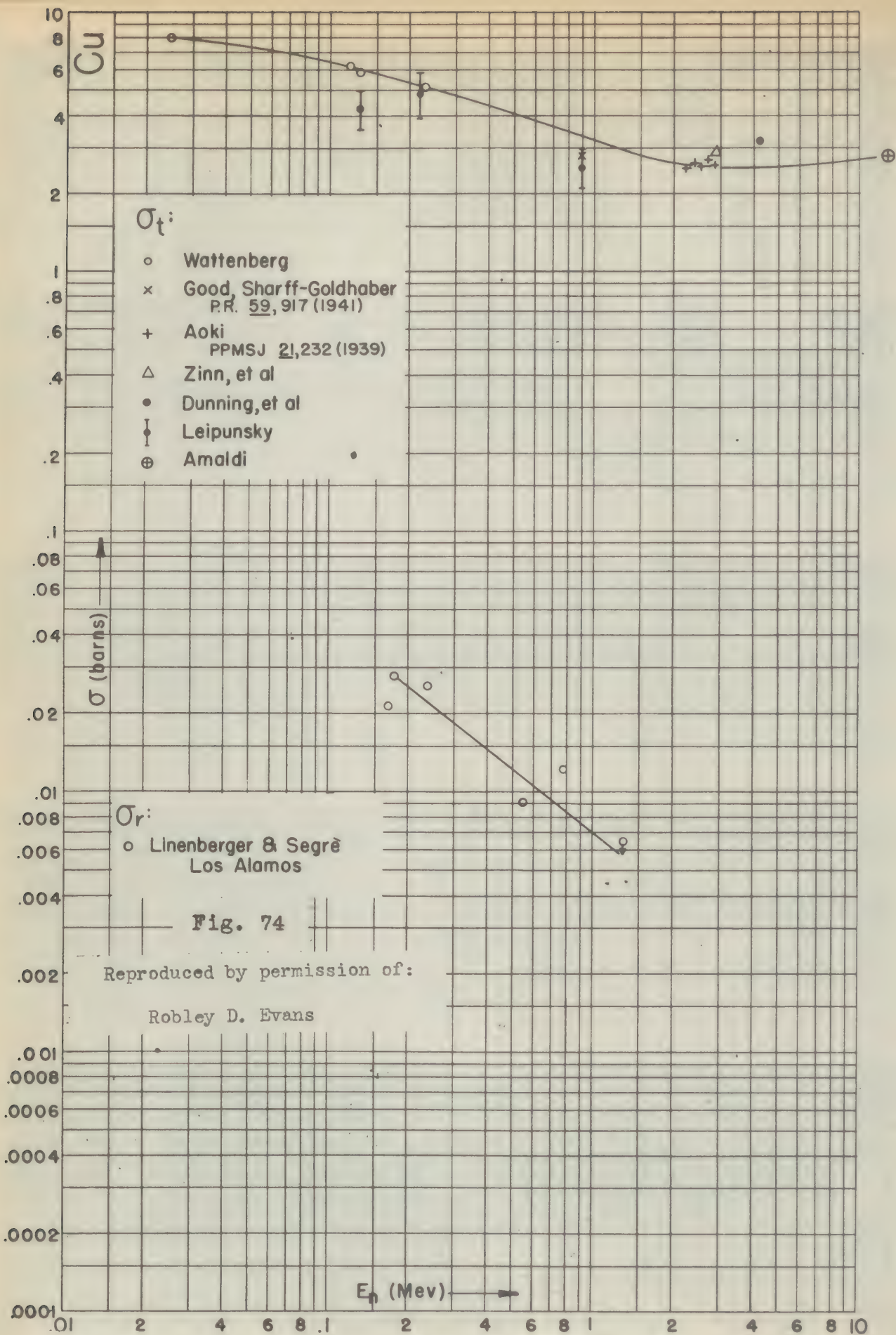
$\sigma_t$   
 • Columbia Velocity Selector  
 x Hanstein  
 P.R. 59,489 (1941)

Fig. 73

Reproduced by permission of:  
 Robley D. Evans









Cb

$\sigma_t$

• Columbia, Velocity Selector

Fig. 75

Reproduced by permission of:

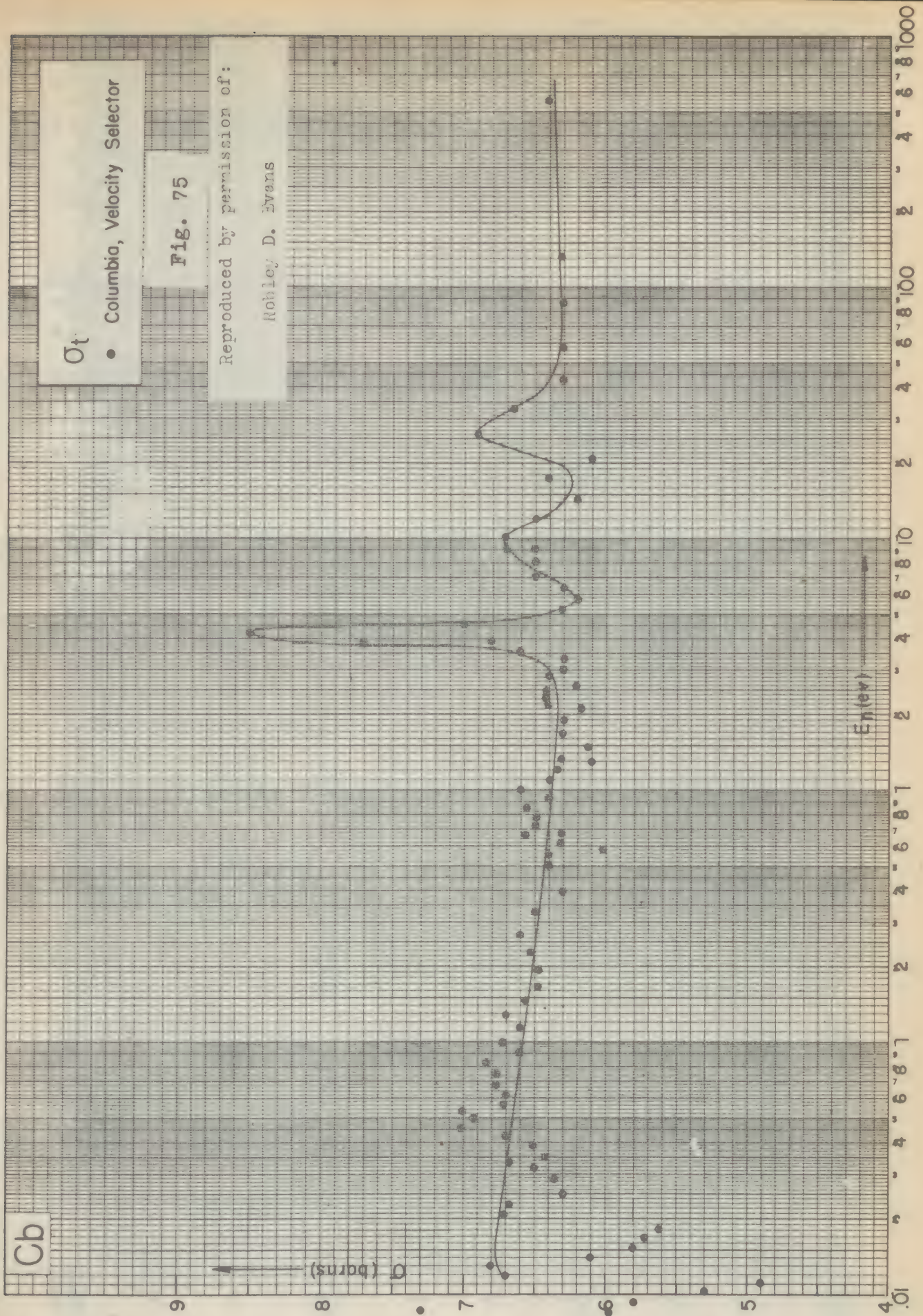
Robley D. Evans

$\sigma$  (barns)

$E(\text{ev})$

243

5669





Rh

$\sigma_t$  (bars)

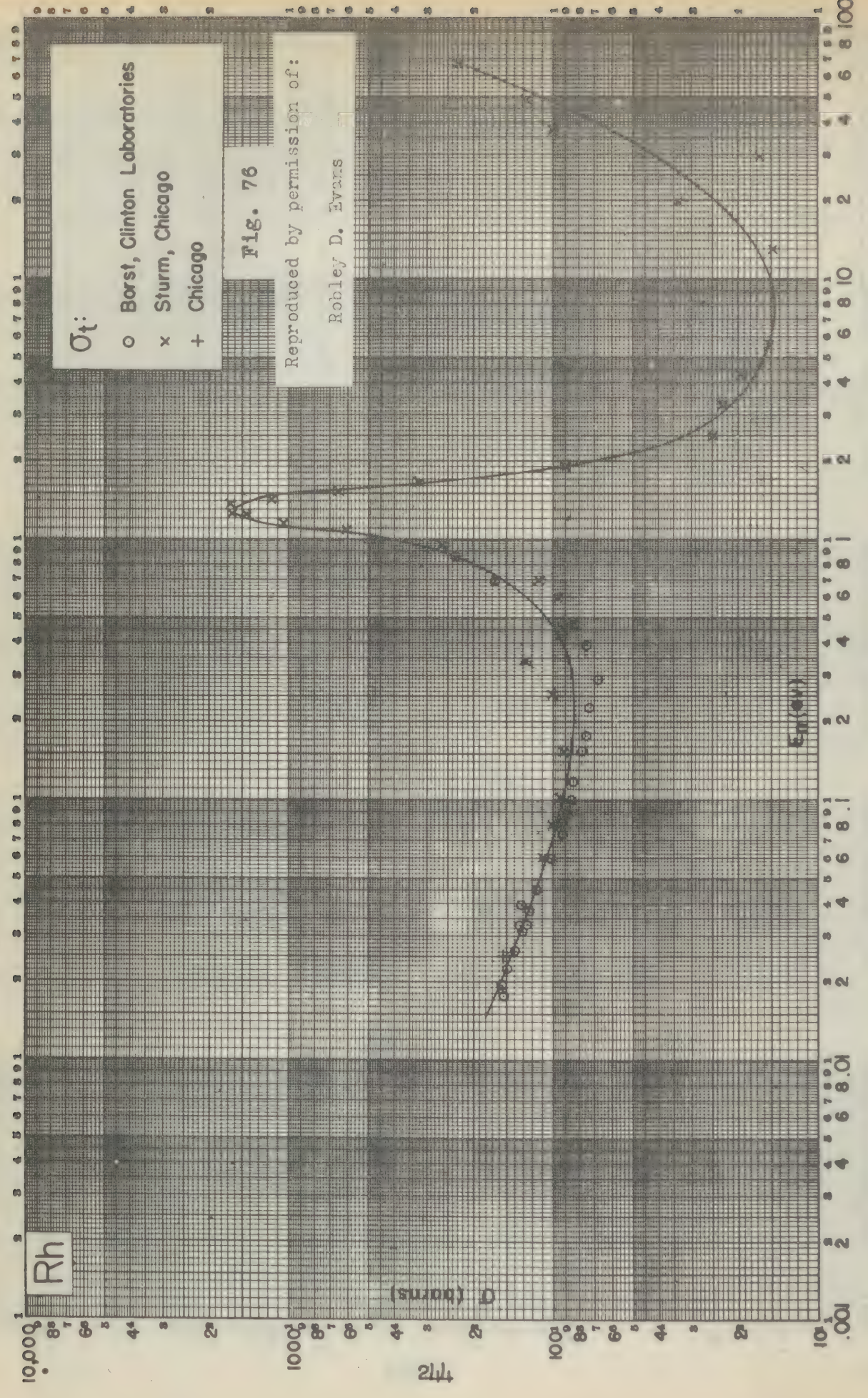
$E_n$  (eV)

$\sigma_t$ :

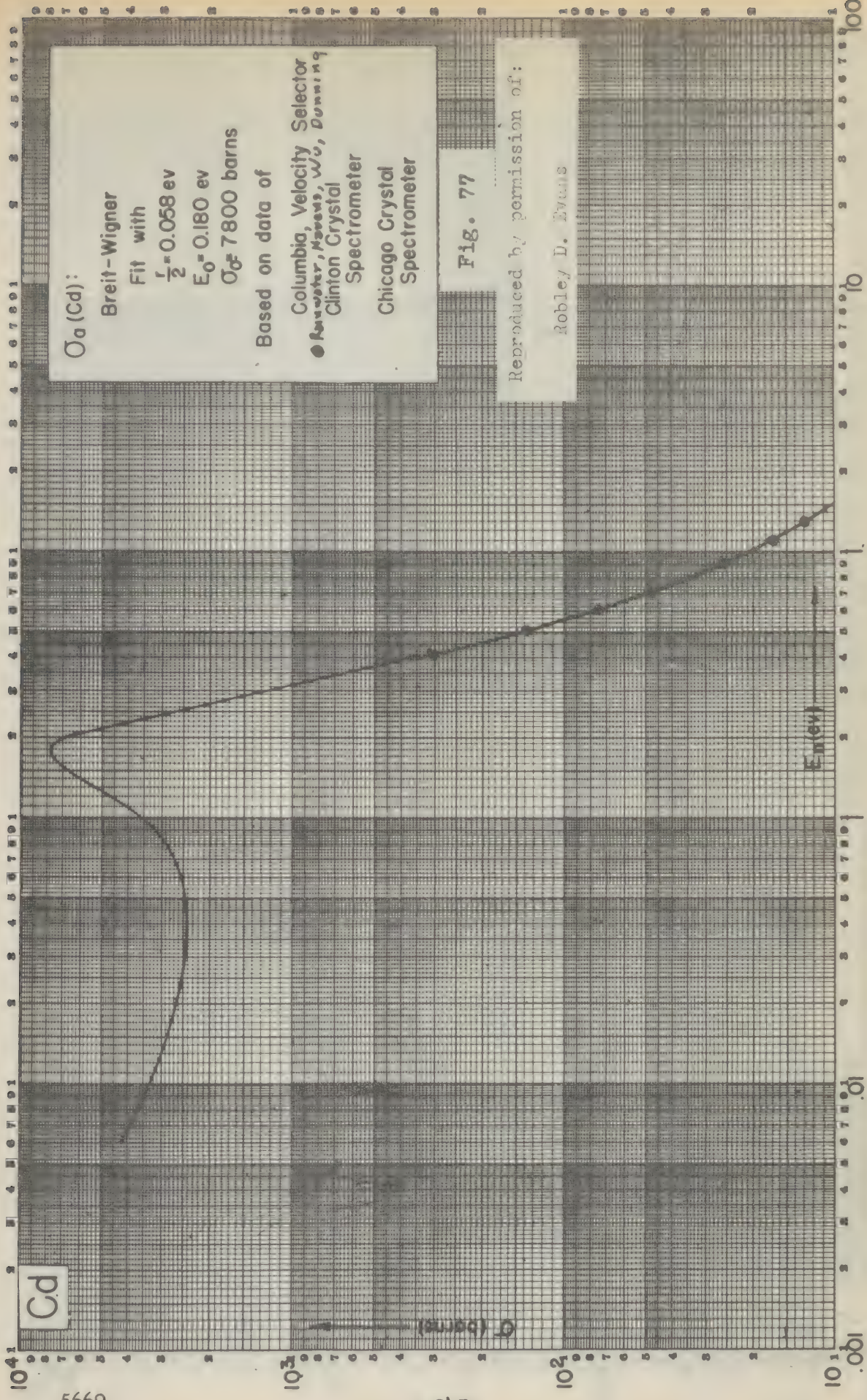
- Barst, Clinton Laboratories
- × Sturm, Chicago
- + Chicago

Fig. 76

Reproduced by permission of:  
Robley D. Evans







$\sigma_a$  (Cd):

Breit-Wigner

Fit with

$\frac{\Gamma}{2} = 0.058 \text{ eV}$

$E_0 = 0.180 \text{ eV}$

$\sigma_0 = 7800 \text{ barns}$

Based on data of

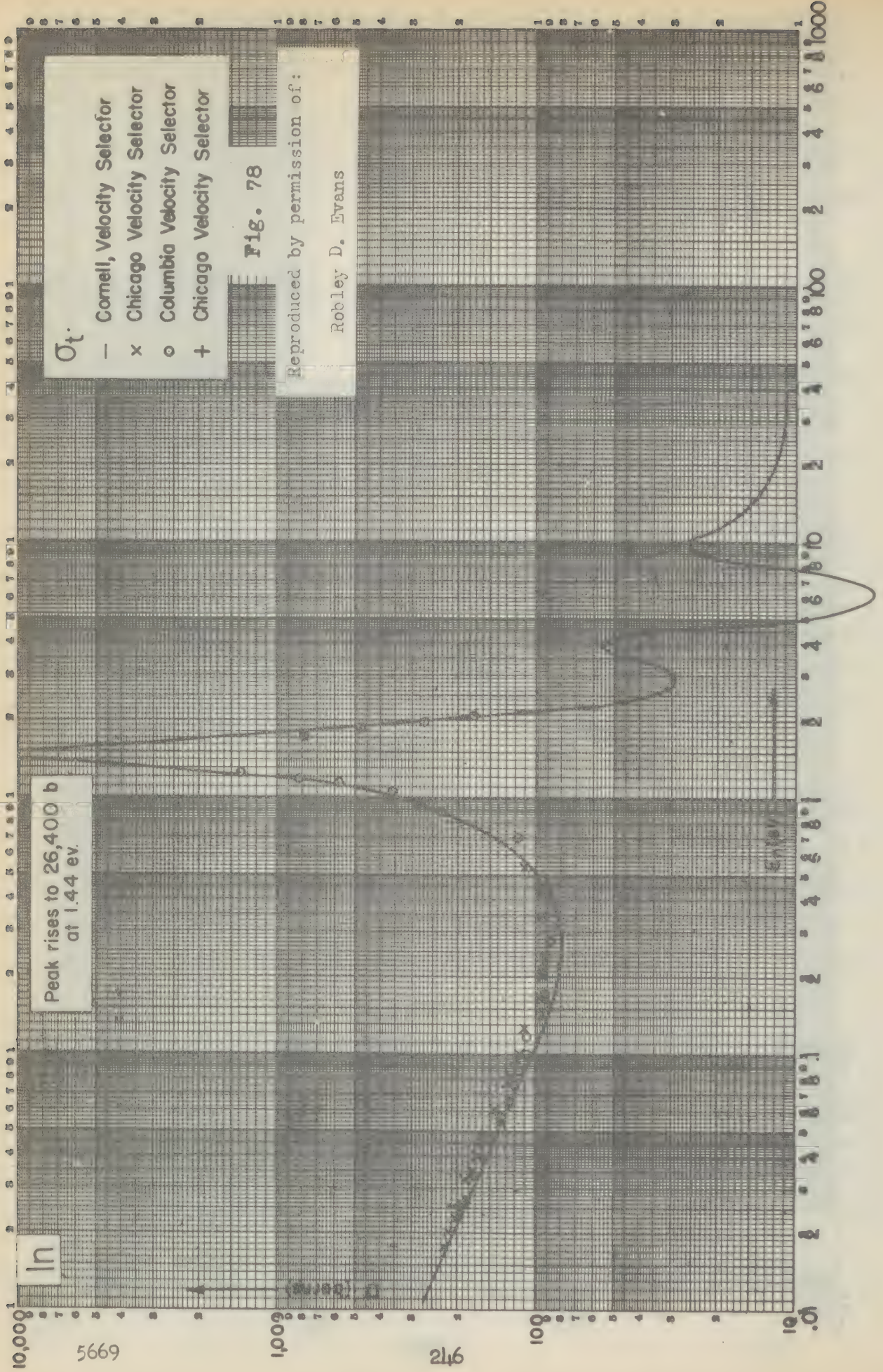
- Columbia, Velocity Selector
- Clinton Crystal Spectrometer
- Chicago Crystal Spectrometer

Fig. 77

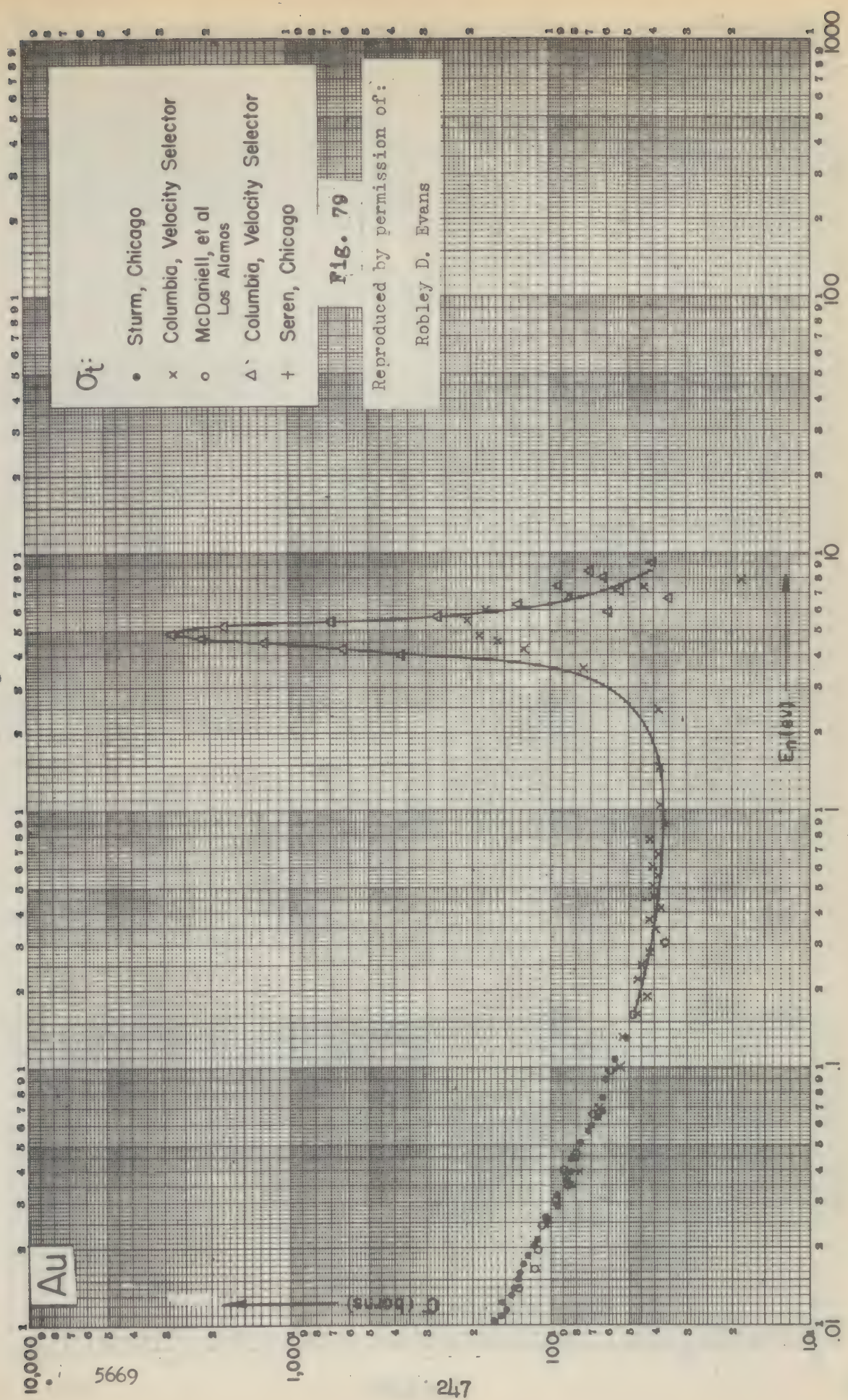
Reproduced by permission of:

Robley D. Evans

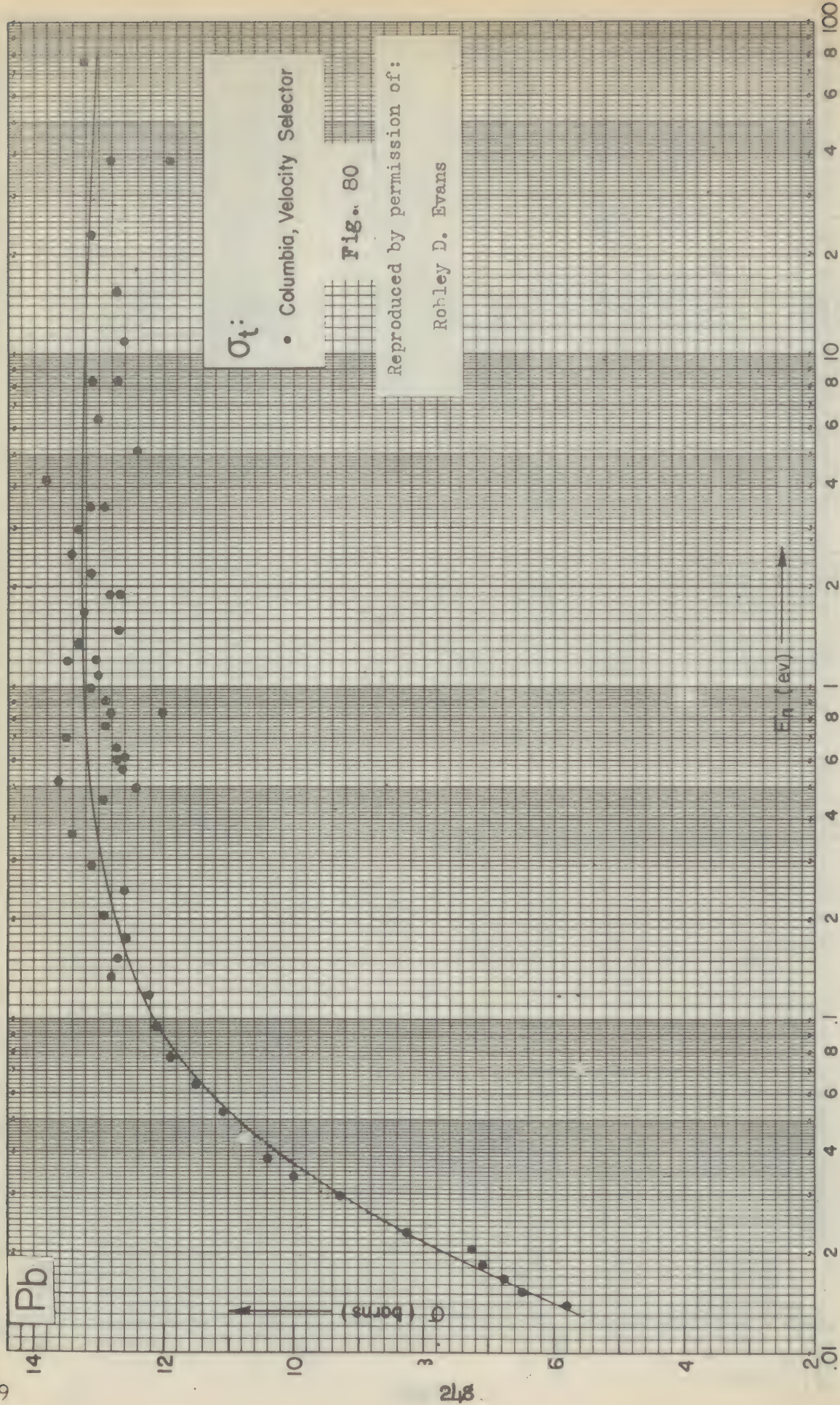












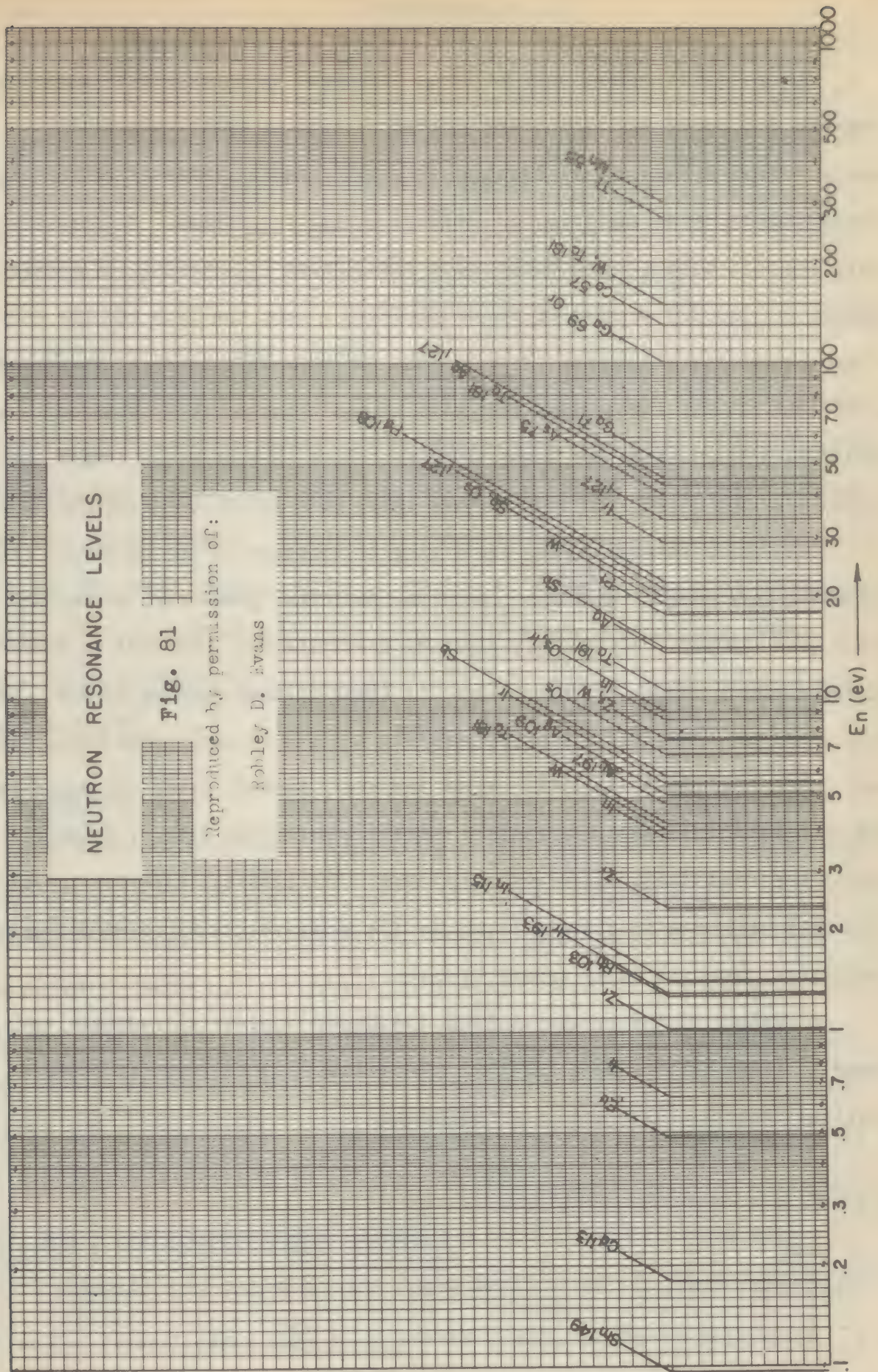


# NEUTRON RESONANCE LEVELS

Fig. 81

Reproduced by permission of:

Robley D. Evans





Radioactivity refers only to those processes by which unstable nuclei decay to form known stable nuclear species by loss of their excitation energy. These processes are distinct from the primary processes of nuclear interaction in which unstable, or excited, nuclei are formed. Radioactive decay proceeds with a fixed rate wholly independent of external influences whereas the primary process of formation depends upon the type and the energy of the bombarding radiation. In addition, the primary process of formation of an excited nucleus takes place in a time of the order of  $10^{-10}$  seconds or less while the probable time for decay after formation is enormously longer and varies over the range from  $10^{-7}$  seconds (RaD) to  $\sim 4.4 \times 10^{17}$  seconds (Th).

All known unstable nuclei decay only by emission of one or more of the following radiations: negatron, positron, neutrino, gamma-ray, alpha particle, and neutron. In general, decay or de-excitation, proceeds by several discrete energy steps, or transitions, to lower nuclear quantum levels. In most cases this involves a charged particle and one or more gamma rays. In many instances, particularly in medium and heavy nuclei, decay may occur by one of several alternative processes involving different sets of quantum levels and, sometimes, different radiations. The probabilities for the alternative processes is given directly by the observed fractions of different radiations, when the decay scheme is known.

A summary of the processes which are known to occur in radioactive decay is given below. More detailed discussions will be found in other sections describing the specific radiations.

### 1. Negatron emission (beta decay)

A beta particle and neutrino are emitted simultaneously and share, in varying proportion, the total fixed energy corresponding to a discrete level



transition. The observed beta kinetic energy varies from 0 to a well defined maximum, corresponding to the total transition energy. The residual, or daughter, nucleus is greater in charge by one unit of  $e$  and the exact atomic weight is diminished by only the mass equivalent of the maximum kinetic energy of the beta particles. The statistics remain unchanged but the nuclear spin is reduced by an integral multiple of  $h/2\pi$ .

## 2. Positron emission (beta decay)

A positron and a neutrino are emitted simultaneously and share in any proportion, the total discrete energy of the level transition. The observed positron kinetic energy may take any value from zero up to the well defined total transition energy. The residual atom is smaller in charge by one unit of  $e$  and its exact atomic weight is diminished by an amount equal to the mass equivalent of the maximum kinetic energy plus twice the electron rest mass. The statistics remain unchanged but the spin is reduced by an integral multiple of  $h/2\pi$ .

## 3. K capture.

An alternative process to positron decay, either K-capture or positron emission may occur for the same level transition (transformation, proton  $\rightarrow$  neutron) when energetically possible. Unlike positron decay, however, a monoenergetic neutrino is emitted. Following K capture, K x-radiation is emitted. The residual atom is smaller in charge by one unit of  $e$  and its exact atomic weight diminished by the mass equivalent of the kinetic energy carried off by the neutrino. The statistics of the nucleus remain the same but the spin is reduced by an integral multiple of  $h/2\pi$ .

## 4. Isomeric transition (gamma emission).

Gamma rays are always mono-energetic for any one nuclear level transition but several gamma rays of different energy,  $h\nu$ , may be emitted in

cascade in the decay of a single atom. The charge of the residual nucleus remains unaltered, the spin is reduced by an integral multiple of  $\hbar/2i$  and the exact atomic weight is reduced by the amount  $h\nu/c^2$ .

### 5. Internal conversion.

Although internal conversion is not part of the decay process, it is frequently observed to accompany gamma emission, particularly in heavy elements. I.C. is the photoelectric absorption of a gamma ray by an orbital electron of the atom from whose nucleus the gamma ray is emitted. K electrons have the highest probability for emission, L electrons next, etc. The electron is ejected with a kinetic energy equal to the gamma ray energy  $h\nu$ , minus the binding energy (ionization potential) of the electron in the residual atom. This is accompanied by characteristic K, L, etc. X-radiation. The probability for the process is given by the conversion coefficient,  $\alpha$ , which is numerically equal to the ratio of the number of gamma rays of a particular energy to the number of photoelectrons ejected by this radiation, i.e.,

$$\alpha = N_K + N_L = \dots / N_\gamma + N_K + N_L + \dots$$

where  $N_\gamma$ ,  $N_K$ , ... are the observed numbers of gamma rays, and K, L, ... electrons.

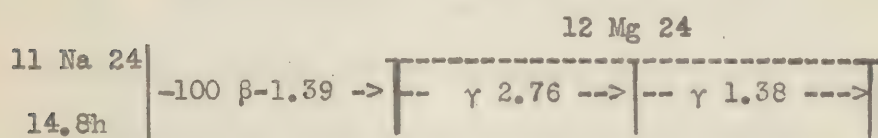
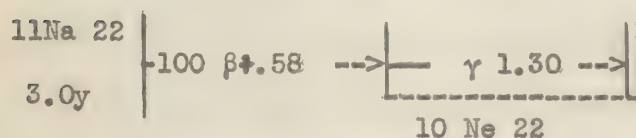
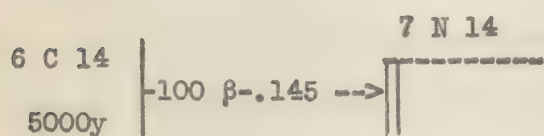
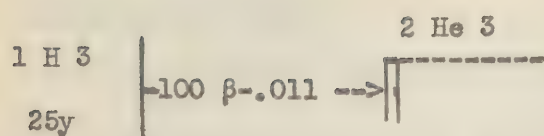
### 6. Alpha decay.

With a single exception, (Li), alpha particle emission is always monoenergetic. Although only one alpha particle is emitted per disintegration many energy groups may be observed corresponding to different, and more or less probable level transitions in the same species of nucleus. The residual atom is smaller in charge by two units of  $e$  and diminished in mass

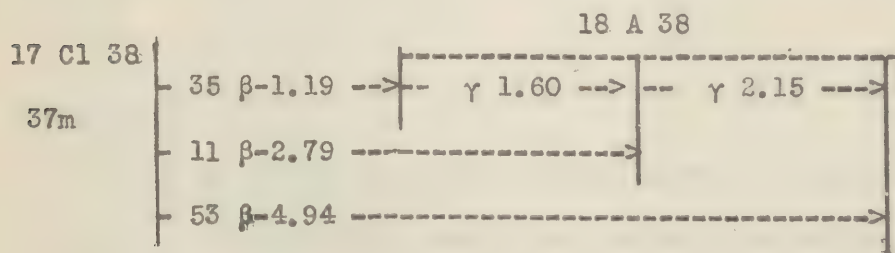
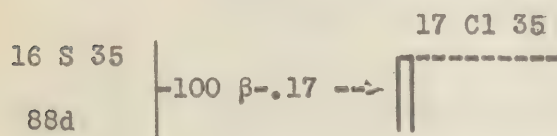
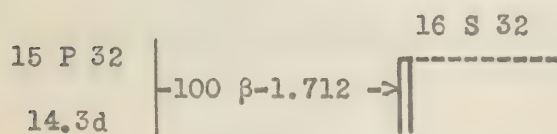


by an amount approximately equal to the rest mass of the alpha particle plus the kinetic energies of the particle and recoil nucleus, plus the rest mass of two electrons. Neither the spin nor statistics is altered by alpha decay.

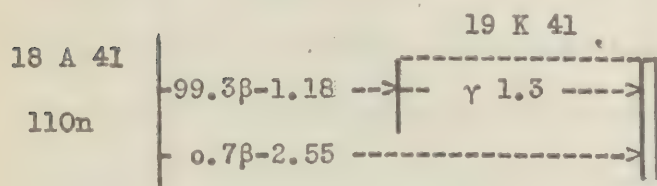
# DECAY SCHEMES FOR RADIOACTIVE ISOTOPES



(1)

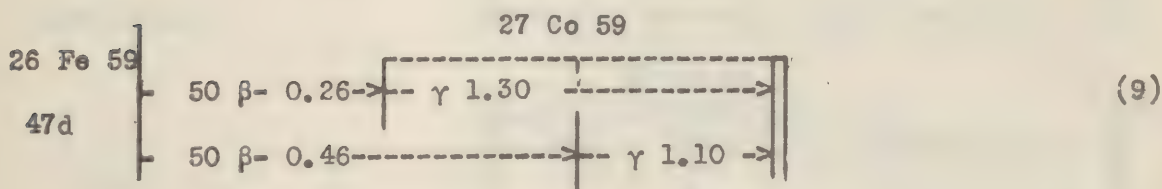
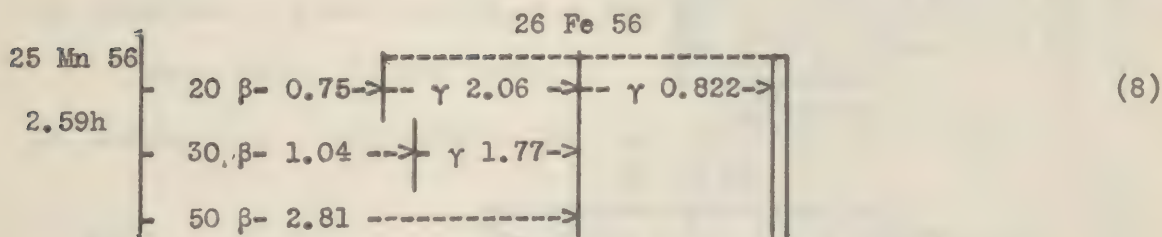
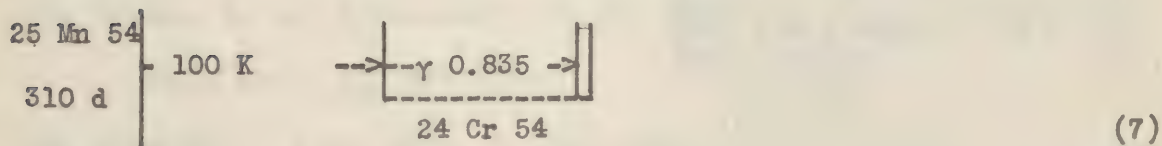
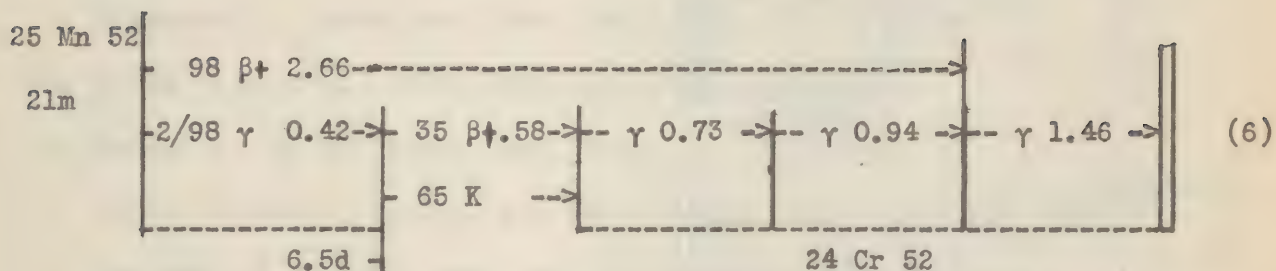
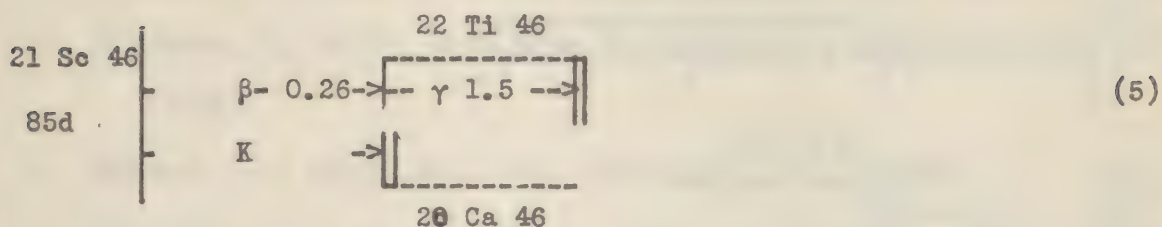
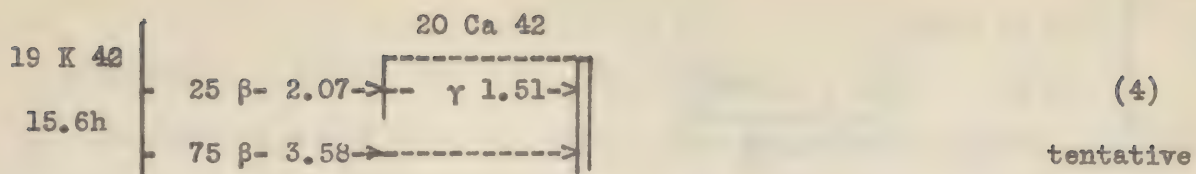


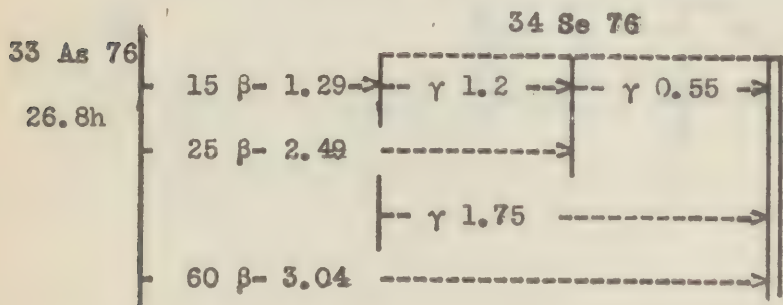
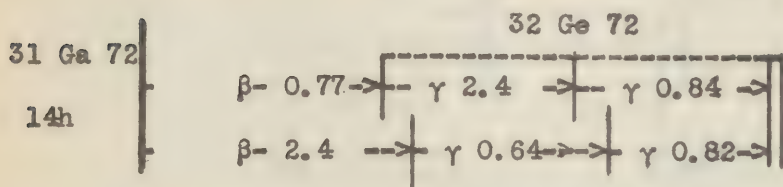
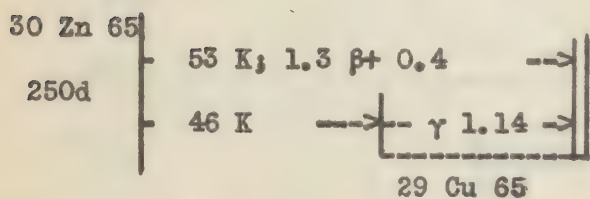
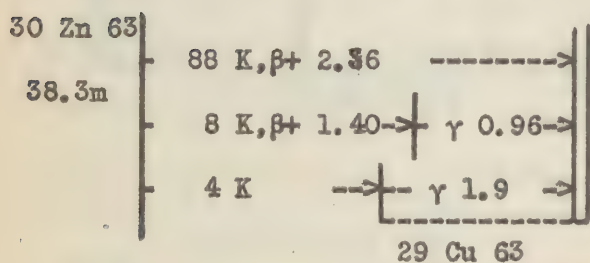
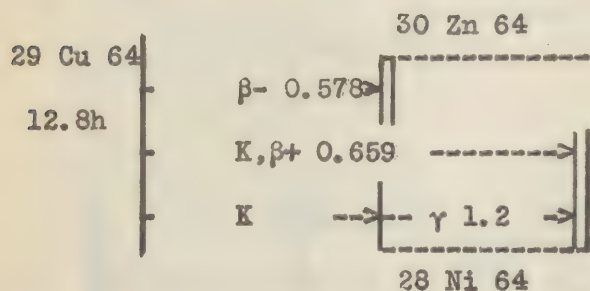
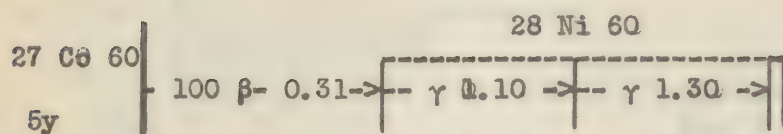
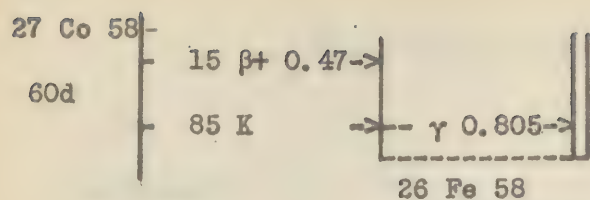
(2)



(3)







(10)

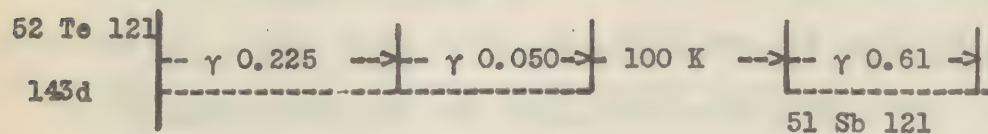
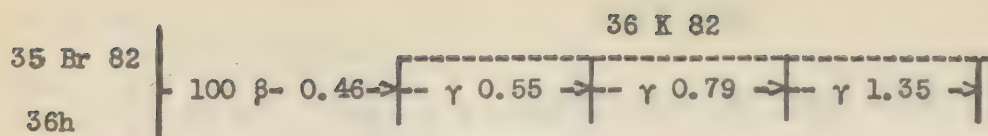
(tentative)

(11)

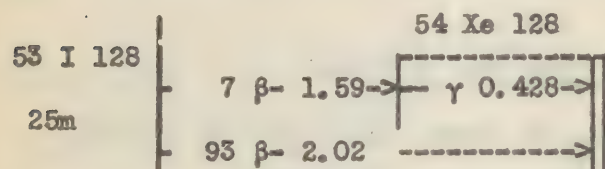


### References

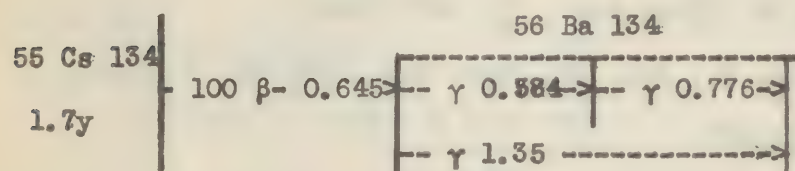
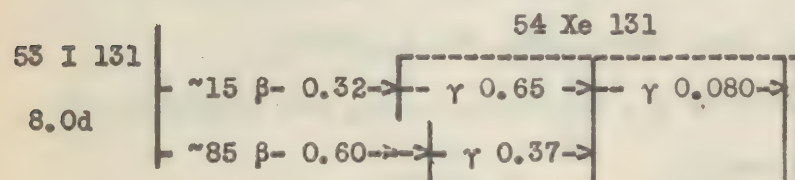
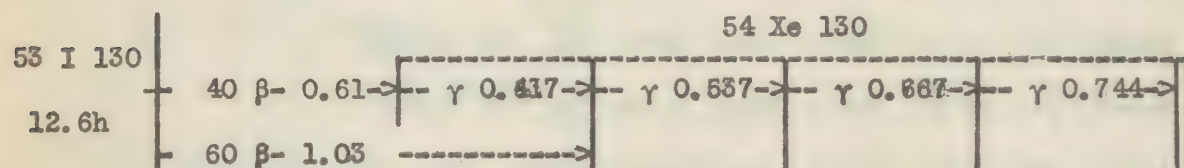
1. Siegbahn, K., Phys. Rev., 70, 127 (1946)
2. Siegbahn, K., and Hale, N., Arkiv. Mat. Ast. Fysik, 32A, No. 9 (1945)
3. Bleuler, E., Boltman, W., and Zunti, W., Helv. Phys. Acta., 19, 419 (1946)
4. Siegbahn, K., Arkiv. Mat. Ast. Fysik, 34A, No. 10 (1946); 34B, No. 4 (1946)
5. Meitner, L., Arkiv. Mat. Ast. Fysik, 32A, No. 6 (1945)
6. Osborne, R. K., and Deutsch, M., Bul. Am. Phys. Soc., 22, 11 (1947)
8. Siegbahn, K., Arkiv Mat. Ast. Fysik, 33A, No. 10 (1946)
- 9a. Bradt, H., et al. Helv. Phys. Acta, 19, 219 (1946)
- 9b. Bradt, H., et al. Helv. Phys. Acta, 19, 221 (1946)
10. Allen, Mitchell, Turney, and Ramsey, Phys. Rev., 71, 324 (1947)
11. Siegbahn, K., Arkiv. Mat. Ast. Fysik, 34A, No. 7 (1946)
12. Bärson, S. B., Bittencourt, P. T., Buffield, R. B., and Goldhaber, M. Phys. Rev., 70, 565 (1946).
13. Siegbahn, K., and Hale, N. Phys. Rev., 70, 133 (1946)
14. Siegbahn, K., and Deutsch, M., Bul. Am. Phys. Soc., 22, No. 1 (1947); Phys. Rev., 71, 483 (1947)
15. Bradt, H. L., and Scherrer, P. Bul. Am. Phys. Soc., 21, No. 6, 8 (1946)



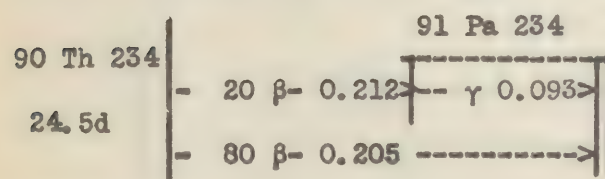
(12)



(13)



(14)



(15)



Table 10. ATOMIC MASS AND SPIN OF RADIOISOTOPES

Z	Element	A	Atomic mass 016 = 16.00000		Isotopic spin
0	n	1	1.00893	3.	1/2
1	H	3	3.01700	3.4	1/2
2	He	3	3.01700	4.	-1/2
		5	5.0137	35.	1/2
		6	6.0209	50.	1
3	Li	5	5.0136	C	-1/2
		8	8.2502	7.	1
4	Be	6	6.0219	100. C	-1
		7	7.01916	7.	-1/2
		8	8.00785	7.	0
		10	10.01677	8.	1
5	B	9	9.01620	7.	-1/2
		12	12.0190	70.	1
6	C	10	10.0210	30. C	-1
		11	11.01495	9.	-1/2
		14	14.00767	5.	1
7	N	13	13.00988	7.	-1/2
		16	16.011	200.	1
8	O	15	15.0078	40.	-1/2
9	F	17	17.0075	30.	-1/2
		18	18.0065	60.	0
		20	20.0087	100.	1
10	Ne	19	19.00781	20.	-1/2
		23	23.0013	C	3/2

Z	Element	A	Atomic mass			Isotopic spin
			016 = 16.00000			
11	Na	21	21.0035		C	-1/2
		22	21.9999	50.		0
		24	23.99745	45.	S1	1
			23.99893		S2	
		25	24.9967		C	3/2
12	Mg	23	23.0002	40.		-1/2
		27	26.9921	150.		3/2
13	Al	25	24.9981	100.		-1/2
		26	25.9929	150.		0
		28	27.9903	70.		1
		29	28.9893	80.		3/2
14	Si	27	26.9949	90.		-1/2
		31	30.9862	60.		3/2
15	P	29	28.9919		C	-1/2
		30	29.9873	50.		0
		32	31.9827	40.		1
16	S	31	30.9892		C	-1/2
		35	34.9788	100.		3/2
		36	35.978	100.		2
17	Cl	33	32.9872		C	-1/2
		34	33.9801			0
		36	35.9788	100.		1
		38	37.981	300.		2



Z	Element	A	Atomic mass 016 = 16.00000		Isotopic spin	
18	A	35	34.9850		C	-1/2
		37	36.9777		C	1/2
		39	38.9755		C	3/2
		41	40.9770	60.		5/2
19	K	38	37.9790		C	0
		40	39.9760			1
20	Ca	39	38.9811		C	-1/2
22	Ti	45	44.9711		C	
		51	50.9612	100.		
24	Cr	51	50.9613	100.		

Values taken from compilations and calculations by R. D. Evans (private communication) and W. H. Barkas, Phys. Rev. 55, 691 (1939). C indicates calculated mass. S1, Sachs, R. G., Phys. Rev. 70, 572 (1946); S2, Siegbahn, K., Phys. Rev. 70, 127 (1946).

## Table 11 . RADIOACTIVE ISOTOPES

The table of radioisotopes presented here includes nearly all the isotopes reported in the literature up until September 1947. Seaborg's "Table of Isotopes" (Seaborg, G. T., Rev. Mod. Phys. 16, 1 [1944]) was used as the basis for this table since it contains a complete compilation of data up to June 1, 1944. To this has been added more recent values for previously known isotopes and many new activities reported since 1944. The largest single contribution to new activities, as well as revised data for previously existing isotopes, was made through the exhaustive study of fission products by the Atomic Energy Commission (Manhattan District, Corps of Engineers) and reported by the Plutonium Project, (J. Am. Chem. Soc. 68, 2410 [1946]). Data quoted from this source is indicated by the reference number P47 but no specific references are given. The reader is referred to the original report for a complete list of references.

The table presented here cannot be regarded as complete since many new activities, particularly for high energy reactions, have not yet been released for publication. The present list, however, comprises a total number of approximately 700 radioactive species.

The nomenclature used here is essentially the same as that employed by Seaborg. Definitions of the terms in the order of the column in which they appear are given below.

Column 1: atomic number, Z.

Column 2: element; \* indicates natural activity.

Column 3: atomic weight, A.

Column 4: class;

A. Z and A certain



- B. Z certain, A probable
- C. Z certain, one of a few possible isotopes
- D. Z probable
- F. insufficient evidence
- G. probably in error

Column 5: type of radiation;

$\alpha$  = alpha particle

$\beta^-$  = negatrons

$\beta^+$  = positrons

$e^-$  = internal conversion electrons

$\gamma$  = gamma rays

K = K capture

IT = isomeric transition

Column 6: half-life; seconds, s, minutes, m, hours, h, years, y.

Column 7: energies of particles. All values given for beta particles refer to the maximum energy. When values are preceded by  $e^-$  or  $\alpha$ , they refer to conversion electrons and alpha particles respectively. When more than one particle is emitted per disintegration, each value is separated by a comma; the energies reported by one reference are separated from another set by a semi-colon.

spect = magnetic spectrograph or similar arrangement.

Cl Ch = cloud chamber

Abs = absorption (in Al, Pb, etc.)

Coincid =  $\beta$  -  $\gamma$  coincidence counters

Coincid abs =  $\beta$  -  $\gamma$  coincidence with absorbers

Column 8: gamma ray energies. Values separated by semi-colons indicate two independent measurements reported.

abs = absorption (in Al, Pb, etc.)

Cl Ch recoil = secondary electrons observed in cloud chamber in magnetic field.

Cl Ch pair = pair formation observed in cloud chamber in magnetic field.

spect = secondary electrons measured by magnetic spectrograph.

spect conv = conversion electrons measured in magnetic spectrograph.

abs of  $e^-$  = absorption of conversion electrons.

coincid =  $\gamma$  -  $\gamma$  coincidence.

coincid abs = secondary electrons measured with absorbers and in coincidence.

Column 9: nuclear reaction. Bombarded element is given first, followed by incident and outgoing particles in parentheses and separated by comma. The symbols fiss, Th-n, U-n, and Pa-n indicate formation by fission. Some inconsistency in notation is found here since fiss refers to any isotope resulting from fission, whether it is a direct fission fragment or one of the chain activities, whereas Th-n, U-n, and Pa-n, indicate only primary fission fragments but are sometimes substituted by "fiss".



Isotope Z El	Class A	Type of Radi- ation	Half-life	Energy of Radiation in mev Particles	Gamma Rays	Produced by
1 H	3 A	$\beta^-$	25 y (O4, P46)	0.015 (O3, N6) abs cl ch		D(d, p) (A7, A16) Be(d, H <sup>3</sup> ) (O6, A16) Li(n, H <sup>3</sup> ) (O4) B(n, H <sup>3</sup> ) (C15) N(n, H <sup>3</sup> ) (C15)
2 He	6 A	$\beta^-$	0.8 s (B1)	3.7 (B1, B2) cl ch		Be(n, $\alpha$ ) (B1, P1, B3, S81) (Li) (n, p) (K1)
3 Li	8 A	$\beta^-, \alpha$	0.85 s (S81) 0.88 s (L1)	3.5 (S81) abs al 12 ( $\beta^-$ ) (B4) cl ch		Li(d, p) (C1, L1, R14 D1) B(n, $\alpha$ ) (L24) (Li) (n, $\gamma$ ) (K1) Li(d, n) (R1, R13, Z1) B(p, $\alpha$ ) (R1, M1) Li(p, n) (H30, H2)
4 Be	7 A	K, $\gamma$	52 d (R13, A18, P46)		0.485 (Z1) coincid abs; .55 (P46)	Be(d, p) (M22, L77)
5 B	10 A	$\beta^-, \gamma$	1.3 x 10 <sup>6</sup> y (L77, M22)	.65 (L77) abs Al .56 (P46)	< 0.5 (M22) abs	B(d, p) (C2, F1, B5)
6 C	12 A	$\beta^-$	0.022 s (C2, B22)	12 (B4) cl ch		B(p, n) (B27, D26) B(d, n) (F1, C4, Y1) B(p, $\gamma$ ) (C3, B23) B(p, n) (B23) N(p, $\alpha$ ) (B23) C(n, 2n) (P2) C( $\gamma$ , n) (B74) N( $\gamma$ , p2n) (B74) O( $\gamma$ , n) (B74)
7 C	10 A	$\beta^+$	8.8 s (B27, D26)	3.4 (D26) cl ch		
8 C	11 A	$\beta^+$	20.5 m (S8, T8)	0.95 (D26) cl ch		

Isotope		Type of Radiation	Energy of Radiation in mev			Produced by
Z	El A		Half-life	Particles	Gamma Rays	
C	14 A	$\beta^-$	4700y P46)	0.145(R21)abs	No $\gamma$ (R21)	C(d,p) (R17,R21) N(n,p) (R21)
7 N	13 A	$\beta^+, \gamma$	10.13m	0.92, 1.20(L22) spect 1.24 (S80) spect	0.28(R2) cl ch re- coil (A).515 (S80) abs. (annihilation $\gamma$ )	C(d,n) (H3, Y1, C4, F1, S80) C(p, $\gamma$ ) (He, C4) B( $\alpha$ ,n) (El, R3) N(n,2n) (P2, H44) N(d,H3) (B7) N( $\gamma$ ,n) (B74)
N	16 A	$\beta^-, \gamma$	7.3 s C5,N1)	9.5, 4.4(S81) abs al	4 (P46,S81)	N(d,p) (F1) O(n,p) (C5,S81) F(n, $\alpha$ ) (N1,P1,N4)
8 O	15 A	$\beta^+$	126 s (M3,B20)	1.7(F1) cl ch		N(d,n) (M3,F1) O( $\gamma$ ,n) (B20, H44) O(n,2n) (P2) N(p, $\gamma$ ) (D2) C( $\alpha$ ,n) (K3) O( $\gamma$ ,n) (B74)
O	19 A	$\beta^-$	31 s (N1)	3.3(S82) 4.1(P46)	1.6(P46)	F(n,p) (N1,A1)
9 F	17 A	$\beta^+$	70 s (N2)	2.1(K4) cl ch		O(d,n) (N2,F1) N( $\alpha$ ,n) (R3) O(p, $\gamma$ ) (D2) F( $\gamma$ ,2n) (B74)



Isotope		Type of	Energy of Radiation in mev		Produced by		
Z	El	Class Radiation	Half-life	Particles	Gamma Rays		
9	F	18	A	$\beta^+$	112 m (S1)	0.7(Y2) cl ch	Ne(d, $\alpha$ ) (S1) O(p,n) (D2) F(n,2n) (P2) O(d,n) (D22, Y2, W2) F(d,H3) (B7, X2) F( $\gamma$ ,n) (H44) F( $\gamma$ ,n) (B74) Na( $\gamma$ , $\alpha$ n) (B74)
F	20	A	$\beta^-$ , $\gamma$ (C47)	B50, 12 s (C1)	5.0(F1, B50) cl ch	2.2(B50) cl ch recoil	F(d,p) (F1, C1) F(n, $\alpha$ ) (N1) Na(n, $\alpha$ ) (N1)
10	Ne	19	A	$\beta^+$	20.3s (W7)	2.20(W7) cl ch	F(p,n) (W7)
Ne	23	A	$\beta^-$	40s (A1, B6)	4.1(P21) abs		Na(n,p) (A1, N1, P1) Mg(n, $\alpha$ ) (A1, B6) Ne(d,p) (P21, W24)
11	Na	21	B		23 s (C27)		Ne(p,n) (C27) Ne(d,n) (P21)
Na	22	A	$\beta^+$ , $\gamma$	3.0 y (L3)	0.58(L3) cl ch	1.3(02) spect	Mg(d, $\alpha$ ) (L3) F( $\alpha$ ,n) (L3, M4) Ne(d,n) (L3)
Na	24	A	$\beta^-$ , $\gamma$	14.8 h (V1)	1.39(L21, S49, S86) spect.	1.38, 2.76 (E7, I2, E8, S86) spect	Na(d,p) (L4, V1) Na(n, $\gamma$ ) (A1) Mg(n,p) (A1) Al(n, $\alpha$ ) (A1) Mg(d, $\alpha$ ) (H4) Si( $\gamma$ , 3pn) (B74) Al( $\gamma$ , 2p, n) (B74) Mg( $\gamma$ , p) (B74)

Isotope		Type of	Energy of Radiation in mev			Produced by	
Z	El	A	Class	Radiation	Half-life	Particles	Gamma Rays
Na	25	E	$\beta^-$ , $\gamma$	62 s (H54)	2.8(H54) abs Al	0.035 (H54) abs Al	Mg( $\gamma$ ,p) (H54) Mg( $\gamma$ ,p) (B74) Al( $\gamma$ ,2p) (B74)
12 Mg	23	A	$\beta^+$	11.6 s (W7)	2.82(W7) cl ch		Na(p,n) (W7,D9) Mg( $\gamma$ ,n) (H43, H44) Mg( $\gamma$ ,n) (B74)
Mg	27	A	$\beta^-$ , $\gamma$	10.2 m (H4)	1.8(Cl3) cl ch	0.64, 0.84, 1.02(I2) spect	Mg(d,p) (H4) Mg(n, $\gamma$ ) (Al) Al(n,p) (Al)
13 Al	26	A	$\beta^+$	7.0 s (W7,F2)	2.99(W7) cl ch		Na( $\alpha$ ,n) (M4,F2) Mg(p,n) (W7,D9) Mg(p, $\gamma$ ) (C29) Al( $\gamma$ ,n) (H43, H44, H58) Al( $\gamma$ ,n) (B74)
Al	28	A	$\beta^-$ $\gamma$ (w17)	2.4m(Al,M5, E2)	3.3(C6) cl ch	1.82(I2) spect	Al(d,p) (M5) Al(n, $\gamma$ ) (Al) Si(n,p) (Al) P(n, $\alpha$ ) (Al) Mg( $\alpha$ ,p) (E2,R3) Si( $\gamma$ ,p) (B74)
Al	29	A	$\beta^-$	6.7 m (B25)	2.5(B25) cl ch and abs		Mg( $\alpha$ ,n) (B25, H21, F3) Si( $\gamma$ ,p) (B74) P( $\gamma$ ,2p) (B74)
14 Si	27	A	$\beta^+$	4.9s(K10,C27)	3.74(M21) cl ch; 3.54(B8) cl.ch		Al(p,n) (K8, M21, C27, B8) Mg( $\alpha$ ,n) (K10)
Si	31	A	$\beta^-$	170 m (N3, Al3)	1.8(K4) cl ch	No $\gamma$ (N3)	Si(d,p) (N3) Si(n, $\gamma$ ) (Al) P(n,p) (Al,P2) S(n, $\alpha$ ) (S2,C9)



Isotope Z A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
15 P 29	A	$\beta^+$	4.6 s (W11)	3.63 (W11) cl ch		Si(F,n) (W11) P( $\gamma$ ,2n) (B74)
P 30	A	$\beta^+$	2.55 m(R3,B49)	3.0(B48,B49) cl ch; 3.5(W26) spect		Al( $\alpha$ ,n) (R3,C7) S(d, $\alpha$ ) (S2) P(n,2n) (P2) P( $\gamma$ ,n) (B20) Si(p,n) (B23,B49) Si(He <sup>3</sup> ,p) (A7) P( $\gamma$ ,n) (B74)
P 32	A	$\beta^-$	14.30 d (C8)	1.71 (S86,S49) spect	No $\gamma$ (K4,S86)	P(d,p)(N3) P(n, $\gamma$ ) (A1) S(n,p) (A1) Cl(n, $\alpha$ ) (A1) S(d, $\alpha$ ) (S2) Si( $\alpha$ ,p) (F3)
P 34	A	$\beta^-$ , $\gamma$	12.4 s (P46)	3.2, 5.1 (P46)		P(p,n) (W11,V4) Si( $\alpha$ ,n) (K10) S( $\gamma$ ,n) (H43,H44,H58)
16 S 31	A	$\beta^+$	3.2 s (W11,K10)	3.85 (W11,E4) cl ch		Cl(n,p) (A3,L6,L58,K13) S(d,p) (C25,K13) Cl(d, $\alpha$ ) (K13)
S 35	A	$\beta^-$	87.1 d (H53)	0.107(L6) spect; 0.120(K13) abs A1		S(d,n) (H31) S(p,n) (W11)
S 37	B	$\beta^-$ , $\gamma$	5. m	1.6, 4.6 (P46)	2.6 (P46)	P( $\alpha$ ,n) (F2,R3,B21) S(d,n) (S2) Cl(n,2n) (P2) Cl( $\gamma$ ,n) (B20,H44) S( $\alpha$ ,p n) or S( $\alpha$ ,d) (S45)
17 Cl 33	A	$\beta^+$	2.4 s (W11)	4.13 (W11) cl ch		
Cl 34	A	$\beta^+$	33 m(S2,B21)	2.5 (B21) abs	3.4 (P46)	

Isotope Z El	A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Cl	36	A	$\beta^+$ ; K; $\beta^-$ (G8)	$10^5$ y (G8,05)	0.64( $\beta^-$ )(G8) abs		Cl(n, $\gamma$ )(G8) Cl(d,p)(G8)
Cl	38	A	$\beta^-$ , $\gamma$	37 m (V1)*	1.1, 2.8, 5.0 (W16, W17) spect (W17) coincid abs	1.65, 2.15 (C28, I2) spect	Cl(d,p)(K4, V1) Cl(n, $\gamma$ )(A1, K18, A15) K(n, $\alpha$ )(H5)
18 A	35	A	$\beta^+$	1.88 s (E4)	4.4 (E4, W11) cl ch		Cl(p,n)(W11) S( $\alpha$ ,n)(K10)
A	37	A	K(W57)	34.1 d (W57, W18)		No $\gamma$	Cl(d,2n)(W18) Cl(p,n)(W18) K(d, $\alpha$ )(W18) Ca(n, $\alpha$ )(W18) S( $\alpha$ ,n)(W18)
A	39	G	$\beta^-$	4 m (P2)			K(n,p)(P2)
A	41	A	$\beta^-$ , $\gamma$	110 m (S3)	1.5(K4) cl ch (K.U.)	1.37(R8) cl ch recoil	A(d,p)(S3) K(n,p)(H5) A(n, $\gamma$ )(S3)
19 K	38	A	$\beta^+$	7.7m(H5,R3)	2.3(R3) abs		Cl( $\alpha$ ,n)(H5,R3) Ca(d, $\alpha$ )(H5) K(n,2n)(P2) K( $\gamma$ ,n)(H43,H44)
K	40	(H88,S62) A $\beta^-$ (T31,C61), $\gamma$ (K52) K(75%) (T30)		$1.42 \times 10^9$ y (B71); $4 \times 10^8$ y (T30)	0.40(H83), 0.725 (L6) spect; 1.3 (H87) abs	2(K52) abs Fe	Natural source (T31,C61)
K	42	A	$\beta^-$	12.4 h(H5)	3.5(K4) cl ch	1.5(P46)	K(d,p)(H5) K(n, $\gamma$ )(H5,A1) Ca(n,p)(H5) Sc(n, $\alpha$ )(H5)



Isotope		Type of	Half-life	Energy of Radiation in mev		Produced by
Z	El	A	Class	Particules	Gamma Rays	
K	43	C	$\beta^-$	18 m (W1,W12)		Ca(n,p)(W1,W12)
20	Ca	39	F	4.5 m (P2,W12)		Ca(n,2n(?))(P2,W12)
Ca	39	E		1.06 s (H44)		Ca( $\gamma$ ,n)(H44)
Ca	41	B	K, $\gamma$ , $e^-$ (W12)	8.5 d (W12)	1.1(W12)abs Pb, abs of $e^-$	Ca(d,p)(W12) Ca(n,2n)(W12)
Ca	45	A	$\beta^-,\gamma$	180 d(W12)	0.2,0.9(W12)abs	Ca(n, $\gamma$ )(W12) Ca(d,p)(W12,W5) Sc(n,p)(W12)
Ca	47	D	$\beta^-,\gamma$	5.8 (P46)	1.1(P46)	1.3(P46)
Ca	49	A	$\beta^-,\gamma$	2.5 h(W12)	2.3(W12)abs	0.8(W12)abs Pb
Ca	49	B	$\beta^-$	30 m (W12)		Ca(d,p)(W12) Ca(n, $\gamma$ )(W12) Ca(d,p)(W12) Ca(n, $\gamma$ )(W12)
21	Sc	41	A	0.87 s (K10)	4.94(E4) cl ch	Ca(d,n)(K10,E4)
Sc	42	F	$\beta^+$	13.5 d (W10)	1.4(W10) abs	K( $\alpha$ ,n)(W10)
Sc	43	A	$\beta^+,\gamma$	3.92 h (H90, W10)	0.4,1.4(W10)abs; 1.13 (H1,H90) abs	1.1(W10)abs Pb; 1.65(H1,H90) abs Pb
Sc	44	A	I,T, $e^-,\gamma$ (W10)	2.44 d(P46)	0.27(H9,S19) spect conv; 0.28, 1.33(H1)	Sc(n,2n)(B9,H1) K( $\alpha$ ,n)(W10,H1) Ca(d,n)(W3,S19,H1) Ca(p,n)(D2,D9) Ti(d, $\alpha$ )(W4)

Isotope Z El A	Class	Type of Radiation	Energy of Radiation in meV			Produced by
			Half-life	Particles	Gamma Rays	
Sc 44 A	$\beta^+, \gamma$	3.92 h(W10, H90)	1.5(W10)abs, (S19) Spect; 1.33 (H1, H90) abs	1.33(H90) 1.80(H1)		Sc(n, 2n) (B9, H1) K( $\alpha$ , n) (W10, H1) Ca(d, n) (W3, S19, H1) Ti(d, $\alpha$ ) (H60) Ca(p, n) (D2, D9) Sc( $\gamma$ , n) (B20) Sc44 (52 h) I.T. (W10)
Sc 46 A	$\beta^-, \gamma$ , K(W5)	85 d(W5)	0.26, 1.5( $\beta^+$ ) (W10) abs	1.25(W10) abs Pb 1.5 (M64)		Sc(d, p) (W1, W5) Sc(n, $\gamma$ ) (W1) Ti(d, $\alpha$ ) (W1) Ca( $\alpha$ , p) (W10) Ti(n, p) (W4)
Sc 47 B	$\beta^-$	3.4 d(H90, W10)	0.46(H90)abs al 1.1(W10)abs	No $\gamma$		Ca( $\alpha$ , p) (W10) Ti(n, p) (W10) Ca(d, n) (H90) Ca(p, $\gamma$ ) (H90)
Sc 48 A	$\beta^-, \gamma$ (W10)	44 h(W10, M2)	0.64(S19)spect; 0.57(H1, H90)	1.35(M2, M30) spect; 1.33(H1) (H90) abs		Ti(n, p) (W4, P2, W10, M30) V(n, $\alpha$ ) (W4, P2, W10) Ca(d, 2n) (S19, M2, H1, M30) Ti(d, $\alpha$ ) (H60) Ca(p, n) (H1)
Sc 49 A	$\beta^-$	57 m (W10)	1.8(W10)abs	No $\gamma$ (W10)		Ca(d, n) (W10) Ca49 (2.5 h) $\beta^-$ decay (W10) Ti(n, p) (W10)
22 Ti 45 A	$\beta^+$	3.08 h(A17)	1.2(A17)cl ch			Ca( $\alpha$ , n) (A17) Sc(p, n) (A17) Sc(d, 2n) (A17) Ti(n, 2n) (A17) Ti( $\gamma$ , n) (H45)



Isotope		Type of Class Radiation	Half-life	Energy of Radiation in $\text{MeV}$		Produced by
Z	El			Particles	Gamma Rays	
Ti	51	A	$\beta^-, \gamma$ (W4)	6. m (W4)	1.6 (P46)	Ti(d,p) (W4) Ti(n, $\gamma$ ) (W4, A1)
Ti	51	A	$\beta^-, \gamma$	72 d (W5)	0.36 (W5) abs	Ti(d,p) (W5) Ti(n, $\gamma$ ) (W8)
23	V	47	B	$\beta^+$	33 m (W4, O7)	1.9 (W4, O7) abs
V	48	A	$\beta^+, K, \gamma$ (W5, H60)	16 d (W4)	1.0 (W4) cl ch; 0.58 (H60)	Ti(d,n) (W4) Sc( $\alpha$ ,n) (W6) Cr(d, $\alpha$ ) (W4) Ti(p,n) (D9)
V	49	B	K	600 d (W5)	No $\beta^+$ or $e^-$ (W5)	Ti(d,n) (W5) V(n,2n) (W4)
V	50	A	$\beta^+$	3.7 h (W4)	No $\gamma$ (W5)	Ti(d,n) (W4) Ti( $\alpha$ ,p) (W4)
V	52	A	$\beta^-, \gamma$	3.9 m (W4)	2.05 (D24) abs	V(n, $\gamma$ ) (W4, P2, A1) V(d,p) (W4) Cr(n,p) (W4, P2) Mn(n, $\alpha$ ) (W4, P2, A1)
24	Cr	49	A	$\beta^+, \gamma$	41.9 m (O7)	1.45 (O7) abs, cl ch
Cr	51	A	K, $\gamma$ , $e^-$ (W13)	26.5 d (W13)	0.18, 1.55 (O7) abs Pb	Ti( $\alpha$ ,n) (O7) Cr(n,2n) (O7)
Cr	55	B		1.6-2.3 h (A14, D14)	0.5, 1. (W13) abs Pb abs of $e^-$ 0.33 (P46)	Ti( $\alpha$ ,n) (W13) Cr(d,p) (W13, A14) Cr(n, $\gamma$ ) (W13) Cr(n,2n) (A14) Cr(n, $\gamma$ ) (D14, A14) Cr(d,p) (A14)

Isotope Z El. A	Type of Class Radiation	Half-life	Energy of Radiation in Mev		Produced By
			Particles	Gamma Rays	
25 Mn	51 A $\beta^+$	46 m(L7)	2.0(L7) abs		Cr(d,n)(L7) Cr(p, $\gamma$ )(D2,D4)
Mn	52 A $\beta^+, \gamma$	21 m(L7)	2.2(H6,HL2) cl ch	1.2(H6)	Fe(d, $\alpha$ )(D5,L7) Cr(p,n)(H6,HL2)
Mn	52 A $\beta^+, \gamma, K$ (H6,HL2)	6.5 d(E7)	0.77(H6,HL2) cl ch	1.0(H6)	Fe(d, $\alpha$ )(L7) Cr(p,n)(H6,HL2)
Mn	54 A K, $\gamma$ (L7)	310 d(L7)		0.85(L7) abs Pb; 0.835(D35) spect coincid	Fe(d, $\alpha$ )(L7) Cr(d,n)(L7) V( $\alpha$ ,n)(L7) Cr(p,n)(D9)
Mn	56 A $\beta^-, \gamma$	2.59 h(L7)	0.75, 1.05, 2.86(E12) spect coincid; 1.04, 2.88(T8) spect	0.845, 1.81, 2.13 (E9, E12) spect; 0.800(G3) spect	Mn(n, $\gamma$ )(A1) Mn(d,p)(L7) Fe(d, $\alpha$ )(L7) Fe(n,p)(A1) Co(n, $\alpha$ )(A1) Cr( $\alpha$ ,p)(R3)
26 Fe	53 A $\beta^+$	8.9 m(R3)			Cr( $\alpha$ ,n)(R3) Fe(n,2n)(L20) Fe( $\gamma$ ,n)(H43)
Fe	55 A K, $e^-$	$\sim 4$ y(V4)			Fe(d,p)(L23) Mn(p,n)(V4) Co $\beta^+$ decay(L10)
Fe	59 A $\beta^-, \gamma$	47 d(L20)	0.26, 0.46(D16) spect coincid abs	1.10, 1.30(D16) spect	Fe(d,p)(L20,D16) Co(n,p)(L20)
27 Co	55 A $\beta^+, \gamma$	18.2 h(D5)	1.50(L21) spect	0.16, 0.21, 0.8, 1.2 (C20) cl ch recoil	Fe(d,n)(L10) Fe(p, $\gamma$ )(L9,L10)



Isotope Z El A	Type of Class Radiation	Half-life	Energy of Radiation in mev		Produced By
			Particles	Gamma Rays	
27 Co 56	A $\beta^+$ , $\gamma$ , K (E9)	72 d (L10)	1.2(L10)abs(C17)cl ch coincid; 1.50(E9,E12)spect,coincid	1.7(C17)abs Pb coincid; 1.05(L10)abs Pb;0.845,1.26,1.74,2.01,2.55,3.25(E12)spect coincid	Fe(d,2n)(L10,P3,J1) Ni(d, $\alpha$ )(L10,C17) Fe(a,np)(L10)
Co 57	A K, $\gamma$ , $e^-$ , $\beta^+$ (L10)	270 d (L10)	0.26( $\beta^+$ ) (L10)	0.117,0.130,0.202,0.215,(P3)spect	Fe(d,n)(L9,B24,P4,L10) Fe(p, $\gamma$ )(L10)
Co 58	A $\beta^+$ , $\gamma$ (10%); K (D35); K (90%)(D35)	72 d (L10)	0.4(L10)abs;0.470(E13,D35)spect;(E13),coincid	0.6(L10)abs Pb;0.805(D35)spect coincid	Fe(d,n)(L9,B24,P4,L10) Mn( $\alpha$ ,n)(L9,L10) Ni(d, $\alpha$ )(L11) Fe(p,n)(L9) Ni(n,p)(V5,L10) Fe( $\alpha$ ,np)(L10) Fe(p, $\gamma$ )(L10)
Co 60	A $\beta^-$ , $\gamma$	5.3 y (L10)	0.300(D17)spect coincid abs	1.10,1.30(D17)spect coincid	Co(d,p)(L9,B24,L10,D17,N10) Co(n, $\gamma$ )(R9,L9,L10) Ni(d, $\alpha$ )(L10) Co <sup>60</sup> (10.7 m)I.T. (L10,D17)
Co 60	A I.T, $\alpha$ , $e^-$ (L10,D17); $\beta^-$ , $\gamma$ (D17, N10)	10.7 m (L10)	1.35( $\beta^-$ ) (N10)spect 1.25( $\beta^-$ ) (D52)spect	0.056(I.T.XD17)spect conv; 1.5 (with $\beta^-$ ) (N10)abs Pb	Co(n, $\gamma$ )(H7,L8,L10,D17) Ni(n,p)(H8,L10) Co(d,p)(N10)
Co 61	A $\beta^-$	1.75 $\pm$ .05 h (P45)	1.3 (P45) abs al	No $\gamma$	Ni <sup>61</sup> (n,p)(P45) Co <sup>65</sup> (n, $\alpha$ )(P45) Ni <sup>64</sup> (p, $\alpha$ )(P45) Ni <sup>64</sup> (d, $\alpha$ )(P45)
Co 62	A $\beta^-$ , $\gamma$	13.9 $\pm$ .2 m (P45)	2.5 $\pm$ .1(P45) abs al	1.3(P45)abs Pb	Ni <sup>62</sup> (n,p)(P45)

Isotope		Type of	Energy of Radiation in mev		Produced By			
Z	El	A	Class Radiation	Half-life		Particles	Gamma Rays	
28	Ni	57	A	$\beta^+$	36 h (L11)	0.67(L11)abs	Fe( $\alpha$ ,n)(L11,N11,D18) Ni(n,2n)(L11,N11,D18) Ni( $\gamma$ ,n)(H45)	
	Ni	59	B	K, $\beta^+$	15 y (P46)	.05(P46)	Ni(n, $\gamma$ )	
	Ni	65	A	$\beta^-$ , $\gamma$	2.6 h(L11) (S84)	1.9(L11)abs	1.1(L11)abs Pb; 0.280,0.65,0.93 (G3) spect	Ni(d,p)(L11,N11) Ni(n, $\gamma$ )(H8,N11) Cu(n,p)(H8) Zn(n, $\alpha$ )(H8) Ni(n,2n)(H8,D18,N11)
29	Cu	58,60	C	$\beta^+$	81 s(D4)		Ni(p,n)(D4)	
	Cu	58,60	C	$\beta^+$	7.9 m(D4)		Ni(p,n)(D4)	
	Cu	61	B	$\beta^+$ , K(A4)	3.4 h(T1,R3)	0.9(R3)abs	No $\gamma$ (G2) Ni(d,n)(T1) Ni(p,n)(D4) Ni(p, $\gamma$ )(D4) Ni( $\alpha$ ,p)(R3)	
	Cu	62	A	$\beta^+$	10.5 m(H8)	2.6(C13) c1 ch	Cu(n,2n)(H8) Cu( $\gamma$ ,n)(B20,H44,H45) Co( $\alpha$ ,n)(R3) Ni(p,n)(S18) Ni(p, $\gamma$ )(S18) Cu(d,H <sup>3</sup> )(K22,K14)	
	Cu	64	A	$\beta^-$ , $\beta^+$ , K, $\gamma$ (A4)	12.8 h(V2)	0.58( $\beta^-$ ); 0.66( $\beta^+$ ) (T6,T11,T8) spect	1.2(P46) Cu(d,p)(V2) Cu(n, $\gamma$ )(H8) Ni(p,n)(S18,D4) Zn(n,p)(H8) Cu(n,2n)(H8) Cu( $\gamma$ ,n)(H45)	



Isotope Z El A	Type of Class Radiation	Half-life	Energy of Radiation in mev		Produced By
			Particles	Gamma Rays	
Cu 66	A $\beta^-$	5 m(A1)	2.9(S5)cl ch(KU); 2.58(G15)		Cu(n, $\gamma$ )(A1) Zn(n,p)(H8) Ga(n, $\alpha$ )(C5) Cu(d,p)(L31)
30 Zn 63	A $\beta^+, \gamma$	38 m(D4, B20)	2.3(S18)abs, (T11, T8) spect	0.96, 1.9(P46)	Zn(n,2n)(H8, P2) Zn( $\gamma$ ,n)(B20) Cu(p,n)(S18, D4) Ni( $\alpha$ ,n)(R3) Cu(d,2n)(L31, T8)
Zn 65	A $\beta^+, K, \gamma, e^-$	250 d(L12)	0.4( $\beta^+$ )(D9)cl ch	0.45, 0.65, 1.0 (W15, I3) ch ch recoil; 1.14(D10) (M34) spect	Zn(d,p)(L12) Cu(d,2n)(P4) Cu(p,n)(B12) Zn(n, $\gamma$ )(S6) Ga <sup>65</sup> K decay(L10)
Zn 69	A I.T. $\gamma$ (K11)	13.8 h(L12)		0.439(H9, G3) spect conv	Zn(d,p)(L12, K11, V7) Zn(n, $\gamma$ )(T2, L12) Ga(d, $\alpha$ )(L12) Ga(n,p)(L12)
Zn 69	A $\beta^-$	57 m(L12)	1.0(L12)abs	No $\gamma$ (L12)	Zn(d,p)(L12, K11, V7) Zn(n, $\gamma$ )(T2) Ga(d, $\alpha$ )(L12) Ga(n,p)(L12) Zn <sup>69</sup> (13.8 h)I.T.(K11)
Zn 72	A $\beta^-, \gamma$	49 m(P46)	0.3 (P47)		fiss (F47)
31 Ga 64	B $\beta^+$	48 m(B13)			Zn(p,n)(B13)
Ga 65	A $K, e^-$	15 m(A4, L10)		0.054, 0.117 (D9) spect conv	Zn(d,n)(A4, L10) Zn(p, $\gamma$ )(D9)
Ga 66	A $\beta^+$	9.4 h(B13, R3)	3.1(M7)abs		Cu( $\alpha$ ,n)(M7, R3) Zn(p,n)(B13)

Isotope Z El	A	Class	Type of Radiation	Half-Life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Ga	67	A	K, $\gamma$ , $e^-$	83 h(A4)		0.0925, 0.180, 0.297 (H9) spect conv, spect; 0.292(G3) spect; 0.094, 0.174, 0.187, 0.301(C21) spect	Zn(d, n) (A4, G6, V7) Zn( $\alpha$ , p) (M8) Zn(p, n) (B13, V7)
Ga	68	A	$\beta^+$	68 m(R3)	1.9(R3, M7) abs		Cu( $\alpha$ , n) (R3, M7) Ga(n, 2n) (P2) Ga( $\gamma$ , n) (B20) Zn(p, n) (D2, B13) Zn(p, $\gamma$ ) (?) (D2) Zn(d, n) (G6, V7) Ge(d, $\alpha$ ) (S29)
Ga	70	A	$\beta^-$ , $\gamma$	20 m(B20, A1)	1.68(S25) cl ch(K.U.)		Ga(n, $\gamma$ ) (A1) Ga(n, 2n) (P2) Ga( $\gamma$ , n) (B20) Zn(p, n) (D2, V7) Zn( $\alpha$ , p) (M8) Ge(d, $\alpha$ ) (S29) Ge(n, p) (S29)
Ga	72	A	$\beta^-$ , $\gamma$	14.25 h(S6, P47)	0.77, 2.4 abs (A34); 1.71(P47)	2.4(A34) abs Pb .84, .64, .82(M62) 2.25, 1.17, 2.1(P47) 1.17, 2.65(M30) spect	Ga(d, p) (L20) Ga(n, $\gamma$ ) (S6) Ge(n, p) (S29)
Ga	73	B	$\beta^-$	5. h(P47)	1.4(P47)	No $\gamma$	Ge(n, p) (P47) fiss (P47)
Ga	74	D	$\beta^-$	9 d (S29)	0.8(S29)		Ge(d, $\alpha$ ) (S29)
32 Ge	69	E		~195 d(M8)			Zn( $\alpha$ , n) (M8)
Ge	71	A	K, $e^-$ (?) (S30)	11 d(S30)		0.6(S30) abs of e	Ga(d, 2n) (S30) Ge(d, p) (S30)



Isotope		Type of		Energy of Radiation in mev		Produced By
Z	A	Class	Radiation	Half-life	Particles	
Gamma Rays						
Ge	71	A	$\beta^+$	40 h (S30)	1.2 (S30) abs	Zn( $\alpha$ ,n) (M8) Ge(n, $\gamma$ ) (S6,S29) Ge(d,p) (S6,S30,S29) Ga(d,2n) (S30) Ge(n,2n) (S25,S29) Se(n, $\alpha$ ) (S29)
Ge	75	A	$\beta^-$ , $\gamma$ (S30)	89 m (S30)	1.1 (S25,S29) cl ch (K.U.); 1.2 (S30) abs al	Ge(n, $\gamma$ ) (S6,S29) Ge(d,p) (S6,S29,S30) Ge(n,2n) (S29,S30) As(n,p) (S29,S30) Se(n, $\alpha$ ) (S29,S30) Ge(n, $\gamma$ ) (P47)
Ge	77	A	$\gamma$ , $\beta^-$ (S29)	12 h (S30)	1.9 (S25,S29) cl ch (K.U.)	Ge(n, $\gamma$ ) (S6,S29) Ge(d,p) (S29,S30) Se(n, $\alpha$ ) (S30) fiss (P47)
Ge	77	A	$\beta^-$	59 s (P46)	2.8 (P46)	Ge(n, $\gamma$ ) (S6,S29) Ge(d,p) (S29,S30) Se(n, $\alpha$ ) (S30)
Ge	78	D	$\beta^-$ , $\gamma$	2.1 h (P47)	0.9 (P47)	fiss (P47)
As	72	E	$\beta^+$	26 h (V4)		Ge(p,n) (V4)
As	73	D	K, e $^-$ (E10)	90 d (S26)		Ge(d,n) (S26,E10)
As	73	D	$\beta^+$	50 h (S29)	0.6 (S29)	Ge(d,n) (S29)
As	74	A	$\beta^-$ , $\beta^+$ , $\gamma$ (S26)	16 d (S26)	1.3 ( $\beta^-$ ), 0.9 ( $\beta^+$ ) (S26) cl ch (K.U.)	As(n,2n) (S26,Cl1) Ge(d,n) (S26,S29,I4) Se(d, $\alpha$ ) (F8) Ge(p,n) (D9)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
				Particles	Gamma Rays	
As 76	A	$\beta^-$ ; $\beta^+$ ; $\gamma$ $\gamma(?)$ (S23)	26.8 h (W9, W19)	1.1, 1.7, 2.7( ) (S23, W9, W19) ch ch; 0.7, 2.6( ) (S23) cl ch; coincid (M35)	3.2, 2.2, 1.5 (S23) cl ch pair; 1.94, 0.83 (M6) spect; coincid (M35)	As (d, p) (C11, T3) As (n, $\gamma$ ) (C11) Br (n, $\alpha$ ) (C11) Ge (p, n) (V4) Se (n, p) (S26) Se (d, $\alpha$ ) (F8)
As 77	B	$\beta^-$	40 h (P47)	0.7 (P47)		fiss (P47)
As 78	A	$\beta^-$ , $\gamma$	80 m (S9, P47)	1.4 (S26) cl ch (K.U.) 4.1 (P47)	0.27 (S26) abs Pb	Br (n, $\alpha$ ) (S9, C11, S26) Se (n, p) (S26) fiss (P47)
34 Se 75	A	K, $\gamma$ , $e^-$	115 d (F41)		0.50 (D9) spect conv; several 0.3 (K30) spect conv; 4 (F41)	As (p, n) (D9) As (d, 2n) (K30) As (n, $\gamma$ ) (F41)
Se 81	B	I.T., $e^-$ (L30, P47)	57 m (S9, L30) 59 m (P47)		0.099 (H9) spect conv; 0.098 (P47) spect conv	Se (d, p) (S9, L30) Se (n, $\gamma$ ) (S9, H10) Br (n, p) (S9, L30) Se ( $\gamma$ , n) (B20)
Se 81	B	$\beta^-$	19 m (L30)	1.5 (L30) abs		Se (d, p) (S9, L30) Se (n, $\gamma$ ) (S9, H10) Se ( $\gamma$ , n) (B20) Br (n, p) (L30) Se <sup>78</sup> , 81 (57 m) I.T. (L30) fiss (P47)
Se 83	A	$\beta^-$ , $\gamma$	25 m (P47) 30 m (L30)	1.5 (P47) abs Al	0.17, 1.1, 0.37 (P47) abs Pb	Se (d, p) (L30) Se (n, $\gamma$ ) (L30) fiss (P47)
Se 83	A		67 s (P46)	3.4 (P46)		
Se 84	A		$\sim 2$ m (P47)			fiss (P47)



Isotope		Type of Radiation		Energy of Radiation in mev		Produced By	
Z	El A	Class	Radiation	Half-life	Particles		
						Gamma Rays	
35	Br 78	A	$\beta^+, e^-, \gamma$	6.4 m(S9)	2.3( $\beta^+$ )(S9)abs	0.046, 0.108(V7) spect conv	Se(d,n)(S9) As( $\alpha$ ,n)(S9) Br( $\gamma$ ,n)(B20,C5) Br(n,2n)(H10) Se(p,n)(B13,V7)
Br	80	A	I.T., $\beta^-, \gamma$ (S10, V3, V7, G22)	4.4 h(B13)		0.049, 0.037 or 0.025(V7) spect conv; 0.037(G22) abs A1	Br(n, $\gamma$ )(S9, S10, A2) Br(d,p)(S9) Se(p,n)(B13, V7) Br( $\gamma$ ,n)(B20) Br(n,2n)(P2) Th(n(?))(P12, P16)
Br	80	A	$\beta^-, \gamma$	18 m(S9, S10)	2.0(A2) spect	<0.5(B13, S9)abs	Br(n, $\gamma$ )(S9) Br(d,p)(S9) Se(p,n)(B13) Br( $\gamma$ ,n)(B20) Br(n,2n)(P2) Br <sup>80</sup> (4.4 h) I.T.(S10, S31, D20)
Br	82	A	$\beta^-, \gamma$	34 h(S9)	0.465(R6, D21); (D23) coincid	0.547, 0.787, 1.35 (R6, D15) spect; (D23) coincid; 1.0(P47) abs Pb	Br(n, $\gamma$ )(K5, S9) Br(d,p)(S9) Se(p,n)(B13, R7) Se(d,2n)(S9) Rb(n, $\alpha$ )(S9, P2) fiss(P47)
Br	83	A	$\beta^-$	140 m(L30)	1.05(L30)abs 0.9-1.3(P47)abs A1	No $\gamma$ (S9)	Se(d,n)(S9) Se <sup>83</sup> $\beta^-$ decay(S9, L30) Th(n) (B15, L30) U (n) (L30, M9, S35) fiss (P47)

Isotope Z El	Z	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Br 84	35	A	$\beta^-$	30 m(S35) 33 m(P47)	5.3 (P47) 4.5(B30)abs		U(n) (D6,H22,H57, M9,S35,B29) Th(n)(P12) Rb(n, $\alpha$ )(B29) fiss(P47)
Br 85	35	A	$\beta^-$	3.0 m(S35,B29)			U(n)(S35,B29,S43) fiss(P47)
Br 87	35	A	$\beta^-$ (n)(P47)	50 s(S35) 55.6 s(P47)			U(n)(S35,B29,S43) fiss (P47)
Br >82	35	F	$\beta^-$	22 h(B15)			Th(n)(B15)
36 Kr 79,81	36	C	$\beta^+$ (B41)	34 h(B41)	0.4(C41)cl ch 0.9(B46)		Kr(d,p)(C45,S9,C22) Br(p,n)(B41,C41) Se( $\alpha$ ,n)(C45,C22)
Kr 79,81	36	C	I.T.(?)e $^-$ , $\gamma$ ;no $\beta^+$ (C41)	13 s(C41)		0.187(C41)spect conv	Br(p,n)(B41,C41)
Kr 79,81	36	C	I.T.(?)e $^-$ no (C41)	55 s(C41)		0.127(C41)spect conv	Br(p,n)(B41,C41) Se( $\alpha$ ,n(?))(K3)
Kr 83	36	A	I.T.,e $^-$ (L30)	113 m(L30)	e $^-$ :0.032,0.045,0.028, (P47)	0.029,0.046(H9) spect conv	Br $^{83}\beta$ -decay(L30) Se( $\alpha$ ,n)(C45,C22) Kr(d,p)(C45,C22) fiss(P47)
Kr 85	36	A	$\beta^-$ , $\gamma$	4.5 h(C22, P47)	0.85(B30)abs 0.94(P47)	0.17,0.37(P47) abs Pb	Kr(d,p)(S9,C45,C22) Br $^{85}\beta$ -decay(B29,S43) Sr(n, $\alpha$ )(B29) Rb(n,p)(B29) fiss(P47)



Isotope Z, El, A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
				Particles	Gamma Rays	
Kr 85	A	$\beta^-$	$\sim 10$ y (P47)	0.74 (P47) abs A1	No $\gamma$	Kr(n, $\gamma$ ) (P47) fiss (P47)
Kr 87	A	$\beta^-$	74 m (S9) 75 m (P47)	4 (B30) abs		Kr(d,p) (S9) fiss (P47)
Kr 87	C	n (P47) short		n: 0.3 (P47) cl ch 0.25 (P47) abs A1		fiss (P47)
Kr 88	A	$\beta^-$	3 h (L27, H28)	2.5 (W19) cl ch (K.U.)		Br <sup>87</sup> $\beta$ -decay (B29, S43) Th(n) (H29, A5, L27) U(n) (H28, H11, G9, G21, H46) fiss (P47)
Kr 89	A	$\beta^-$	2.5 m (H56)			U(n) (G9, G21, S41, H46, H47) fiss (P47)
Kr 90	A	$\beta^-$	33 s (P47)			U(n) (H28, H46, H47, H56) Th(n) (H29) fiss (P47)
37 Rb 82	B		20 m (H51)			Br( $\alpha$ , n) (H51)
Rb 84	B		6.5 h (H51)			Br( $\alpha$ , n) (H51) Kr(d, n) (H51)
Rb	F		42 m (H51)			Kr(d, n) (H51)
Rb	F		200 h (H51)			Kr(d, n) (H51)
Rb 86	A	$\beta^-$ , $\gamma$	19.5 d (H13)	1.56 (H13) abs; 1.60 (H32) spect	$\gamma$ (P47)	Rb(n, $\gamma$ ) (S9, S20) Sr(d, $\alpha$ ) (H13) fiss (P47)

Isotope		Type of Class Radiation	Half-life	Energy of Radiation in mev		Produced By
Z	El			Particles	Gamma Rays	
Rb 87 (H89, H84)	A	$\beta^-$ (T31, C61), e $^-$ , $\gamma$ (O30)	$6.3 \times 10^{10}$ y (S74)	0.132 (I6) spect.; 0.13 (O30) spect	0.053, 0.082, 0.102, 0.129 (O30) spect conv	Natural source (T31, C61)
Rb 88	A	$\beta^-$	17.5 m (W19)	5.1 (W19) cl ch 4.6 (P47) abs		Rb(n, $\gamma$ ) (S9, P2, S20) Pa(n) (G7) Kr88 $\beta$ -decay (H28, L27, H11, G21, W19, H46) fiss (P47)
Rb 89	A	$\beta^-$ , $\gamma$ (G21)	15.5 m (G9, G21)	3.8 (G21) abs		Kr <sup>89</sup> $\beta$ -decay (G9, G21, S41, H46, H47) fiss (P47)
Rb 90	A	$\beta^-$	short (P47)			fiss (P47)
Rb 91	A	$\beta^-$	short (p47)			fiss (P47)
Rb 92	D	$\beta^-$	80 s (H28)			Kr <sup>90</sup> (0.5 m) decay (H28, H46, H47, H56)
Rb 94	D	$\beta^-$	short (P47)			fiss (P47)
Rb 95	B	$\beta^-$	short (P47)			fiss (P47)
Rb 97	A	$\beta^-$	short (P47)			fiss (P47)
38 Sr 85 Sr 85	A	K, $\gamma$ (D13) I.T. e $^-$ , $\gamma$ (D25)	65 d (D13) 70 m (D25)		0.8 (D13, D25) abs 0.170 (D25) spect conv	Pb Rb(p, n) (D13, D25) Rb(p, n) (D13, D25)



Isotope Z El	A	Class	Type of Radiation	Half-life	Energy of Radiation in mev			Produced By
					Particles	Gamma Rays		
Sr	87	A	I.T., e <sup>-</sup> , $\gamma$ (D11)	2.7 h (D11)		0.37 (D11) spect conv; 0.386 (H9) spect conv		Sr(n,n) (D13, R15, D25, R20) Rb(p,n) (D11) Sr(d,p) (D11) Sr(n, $\gamma$ ) (D11, R15) Y <sup>87</sup> (80 h) K decay (D11, D25) Sr(p,p(?)) (D25) Zr(n, $\alpha$ ) (S46) Sr <sup>87</sup> ( $\gamma$ , $\gamma$ ) (W54)
Sr	89	A	$\beta$ -	55 d (S24) 53 d (P47) 54 d (P47)	1.50 (S24) cl ch; 1.32 (H32) spect; 1.52 (P47) abs Al	No $\gamma$ (S24)		Sr(d,p) (S11, S24) Sr(n, $\gamma$ ) (S11, S24) Y(n,p) (S12) Rb <sup>89</sup> $\beta$ decay (H28, G9, G21, H46, H47) Zr(n, $\alpha$ ?) (S46) fiss (P47)
Sr	90	A	$\beta$ -	25 y (P46, H47)	0.65 (P46) abs Al	No $\gamma$		fiss (H47)
Sr	91	A	$\beta$ -, $\gamma$	9.7 h (P47) 8.5 h (P47)	1.3-3.2 (P46) abs Al	1. (P46)		fiss (Kr parent) (H56, H47, G13, S48) Zr(n, $\alpha$ ) (S48)
Sr	92	D	$\beta$ -	2.7 h (P47)				Rb <sup>90</sup> (80 s) $\beta$ -decay (G13, H47, H56) fiss (P47)
Sr	93	D	$\beta$ -	7 m (P46)				U(n) (Kr parent) (H56, L26, H28, H47)
Sr	95	C	$\beta$ -	~ 2 m (H47)				fiss (Kr parent) (H56, H47)
Sr	97	A	$\beta$ -	short (P47)				fiss (P47)

Isotope		Type of	Energy of Radiation in mev		Produced By			
Z	El	Class Radiation	Half-life	Particles				
39	Y	86	B	K, $\gamma$	105 d(P46)	0.908, 1.81(P46)		
	Y	87	B	I.T., e <sup>-</sup> , $\gamma$ (D25)	14 h(S24, D13)	0.5(D25)abs	Sr(d, n)(S24, D13, D25) Sr(p, n)(D13, D25)	
	Y	87	A	K(D13)	80 h(D25)	No $\gamma$ (?) (D25)	Sr(p, n)(D13, D25) Sr(d, n)(D13, S24, D25)	
	Y	88	A	$\beta$ +	2.0 h(S24)	1.2(S11)cl ch (K.U.)	Sr(d, n)(S11, S24) Y(n, 2n)(S11) Sr(p, n)(D13, D25)	
	Y	88	A	K, $\gamma$ (D25)	105 d(P46)	0.95, 1.92(R12) cl ch; 0.908, 1.89 (D28)spect coincid; Y(n, 2n)(H33) 1.87(S32)Be n; 1.9, 2.8(G10) D- $\gamma$ -n	Sr(p, n)(D13, D25) Sr(d, 2n)(P11, H33) Y(n, 2n)(H33)	
	Y	90	A	$\beta$ -	60 h(S11) 65 h(P47)	2.6(S11)cl ch (K.U.) 2.2(P47)abs Al	Y(d, p)(S11) Y(n, $\gamma$ )(S11, S12) Cb(n, $\alpha$ )(S42, S13) Zr(n, p)(S46, S48) Zr(d, $\alpha$ )(S46) Sr <sup>90</sup> decay(H47) fiss(P47)	
	Y	91	A	$\beta$ - (B30)	57 d(H42, GL3)	1.6(B30)abs	No $\gamma$	Sr <sup>91</sup> $\beta$ -decay (H47, GL3) Zr(n, p)(S48) fiss(P47)
	Y	91	B	I.T., e <sup>-</sup> , $\gamma$	50 m(GL3)	0.61(P47)		Sr <sup>91</sup> $\beta$ -decay(H47, GL3) Zr(n, p)(S48) fiss(P47)



Isotope		Type of		Energy of Radiation in mev		Produced By	
Z	A	Class	radiation	Half-life	Particles	Gamma Rays	
Y	92	D	$\beta^-$ , $\gamma$ (H56)	3.5 h (H56)	3.6 (b30) abs	0.6 (P47) abs Pb 0.7-1.1 (P47) abs Pb	Sr <sup>92</sup> (2.7 h) $\beta^-$ -decay (G13, H47, H56) Zr (n, p) (S46, S48) fiss (P47)
Y	93	B		11.5 h (H47)	3.4 (P46); 3.1 (P47) abs Al	0.7 (P47) abs Pb	Sr <sup>93</sup> (7 m) $\beta^-$ -decay (H47, H56) fiss (P47)
Y	94	C	$\beta^-$ , $\gamma$ (H56)	20 m (H47)			Sr <sup>90</sup> (2 m) $\beta^-$ -decay (H47, H56) Zr (n, p) (S48) fiss (P47)
Y	95	A	$\beta^-$	< 3 h (P46)			fiss (P47) hyp
Y	97	A	$\beta^-$	short (P47)			fiss (P47)
40 Zr	89	A	$\beta^+$ (S12, D13)	78 h (D25)	1.0 ( $\beta^+$ ) (S12) cl ch (K.U.) (D25) abs	No $\gamma$ (D25)	Zr (n, 2n) (S12, S46) Y (1, n) (D13, D25) Mo (n, $\alpha$ ) (S46)
Zr	89	A	$e^-$ , $\gamma$ , I.T. or K (D13, D25)	4.5 m (D25)			Y (p, n) (D13, D25)
Zr	93	D	$\beta^-$	2.5 m (P47)			Zr (n, $\gamma$ ) (S46) Zr (d, p) (S46) Mo (n, $\alpha$ (?)) (S46) fiss (H55, G18)
Zr	95	A	$\beta^-$ , $e^-$ , $\gamma$	65 d (S46) 63 d (P47)	1 (G18) abs; 0.394 (P47) abs Al; $e^-$ : 0.71, 0.90 (P47) spect	0.7-0.94 (G33, P47)	fiss (G18, H39) Zr (n, $\gamma$ ) (S46) Mo (n, $\alpha$ ) (S46)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of radiation in mev		Produced By
				Particles	Gamma Rays	
Zr 97	A	$\beta^-$ , $\gamma$	17 h (G18)	1.9 (S46) abs; 2.1 (P47)	0.8 (P47) abs	Zr(n, $\gamma$ ) (S46) fiss (P47)
Zr 98	E	$\beta^-$	18 m (S46)			Zr(n, $\gamma$ ) (S46)
Zr 98	E	$\beta^-$	6 m (P46)	$\sim 1.5$ (S46) abs; 1.9 (P46)		Zr(d, ?) (S12, S46)
Zr 99	E	$\beta^-$	70 h (S46)	1.17 (S46) cl ch (K.U.)		Zr(n, ?) (S46)
Zr 99	E		5 s (P46)			
41 Cb	E		4 m			Zr(p, n(?)) (D9)
Cb	E		12 m			Zr(p, n(?)) (D9)
Cb	E		38 m			Zr(p, n(?)) (D9)
Cb 90	B	$\beta^+$	21 h	$\sim 1$ . (P46)		Zr(p, n(?)) (D9)
Cb 91	B	K, $e^-$ , $\gamma$	55 d		0.15, 0.94 (P46)	Zr(p, n(?)) (D9)
Cb 92	A	$\beta^-$ , $\gamma$	11 d (S42, S13)	1.38 (S42) cl ch (K.U.); 0.059 (M33)	1.0 (M33)	Cb(n, 2n) (S42, S13) Mo(n, p) (S46) Zr(p, n) (M33)
Cb 92	E	$\beta^-$ , $\gamma$	21.6 h (P46)		0.6 (P46)	
Cb 93	D	I, $\Gamma$ , $e^-$	42 d (P46, S46)		$\sim 0.15$ (S46, M33) abs of $e^-$ ; 0.94 (M33)	Zr <sup>93</sup> $\beta^-$ -decay (S46, H55) Cb <sup>93</sup> (X-ray) (W54)
Cb 94	A	$e^-$ , I, $\Gamma$ , $\beta^-$ , $\gamma$ (S42)	6.6 m (S42)		0.4 (S42) abs Pb	Cb(n, $\gamma$ ) (S42, S13, P2)
Cb 95	A	$\beta^-$ , $\gamma$	37 d (H44)	0.15 (P47), $e^-$ ; 0.75 (P47)	0.75 (P44, P47) abs Pb	fiss (P47)



Isotope Z El A	Type of Class Radiation	Half-life	Energy of Radiation in mev		Produced By
			Particles	Gamma Rays	
Cb 95	A I.T., e <sup>-</sup>	90 h (P47)	0.22 (P47) abs A1		fiss (P47)
Cb 96	B	96 h (P47)			
Cb 97	A $\beta^-$ , $\gamma$	75 m (P47)	1.4 (P47)	0.78 (P47)	<sup>95</sup> Zr $\beta^-$ -decay (G18, S46) Mo (n, p) (S47) fiss (P47)
42 Mo 93	B $\beta^+$ , $\gamma$	6.7 h (P46)			Cb (p, n (?)) (D9)
Mo 93	C $\beta^+$	17 m (B20, S12)	0.3, 0.7 (P46) 2.65 (S46) cl ch (K.U.)	1.6 (P46)	Mo (n, 2n) (H10, S12, S46) Mo ( $\gamma$ , n) (B20)
Mo 99	A $\beta^-$ , $\gamma$	67 h (S14)	1.5 (S14) abs; 1.2, 1.4 (P47) abs A1	0.4 (S14) abs; 0.77, 0.815, 0.84 (S83) spect conv 0.24 (P47) abs Pb	Mo (d, p) (S14) Mo (n, $\gamma$ ) (S14, S12) fiss (H23, H41, P47) Th (n) (H24) Mo (n, 2n) (S46)
Mo 101	A $\beta^-$ , $\gamma$	14.6 m (M25)	1.8 (S40) cl ch (K.U.); 1.0, 2.2 (M38)	0.3, 0.9 (M38)	Mo (n, $\gamma$ ) (S40, S22, S46, M25) fiss (H41, B28, P47)
Mo 102	C $\beta^-$	12 m (H41)			fiss (H41, H55, P47)
Mo	A $\beta^-$	short (P47)			
43 Tc 96	D $\beta^+(?)$ K, $\gamma$	2.7 h (D4)			Cb ( $\alpha$ , n) (K3) Mo (p, n) (D4) Mo (d, n) (S14)
Tc 96	B K, e <sup>-</sup> , $\gamma$	4.2 d (P46)		0.96 (P46)	Cb ( $\alpha$ , n) (K3) Mo (p, n) (D4) Mo (f, n) (S14)
Tc 97	K (?)	>15y (P46)			

Isotope		Type of		Energy of Radiation in mev		Produced By	
Z	El	A	Class	Radiation	Half-life	Particles	Gamma Rays
Tc	97	B	K, e <sup>-</sup> , $\gamma$		93 d (C12, M63)		0.097 (H9) spect conv Mo(d, n) (C12, C24)
Tc	98	C	K, $\gamma$		62 d (C12)		Mo(d, n) (C12, C24)
Tc	99	A	I, T, e <sup>-</sup> , $\gamma$ (SL4)		5.9 h (P47) 6.6 h (SL4)	0.116 (P47) spect; 0.12 (P47) abs	Mo <sup>99</sup> $\beta$ -decay (SL4, H41) fiss (P47)
Tc	99	A	$\beta$ -		2 x 10 <sup>6</sup> y (P47)	0.38 (P46) abs A1	fiss (P47)
Tc	100	D	$\beta$ -		40 h (P46)	0.5 (P46)	
Tc	101	A	$\beta$ -, $\gamma$		14.0 m (M25)	1.1 (S40) cl ch (K.U.); 1.3 (M38)	Mo <sup>101</sup> $\beta$ -decay (S40, S22, S46, H41, M25) fiss (P47)
Tc	102	C	$\beta$ -		< 1 m (H41)		Mo <sup>102</sup> (12 m) $\beta$ -decay (H41)
Tc	104	D	K(?) e <sup>-</sup> , $\gamma$ (E5)		110 h (E3)	0.6 (E3)	Mo(p, n) (E3, E5)
Tc	105	A	$\beta$ -		short (P47)		Mo(p, n) (E3, D4, E5) fiss (P47)
Tc	106	A	$\beta$ -		18 s (D9)		Mo(p, n) (D3, D9)
Tc	107	C	$\beta$ -		< 1.5 m (P47)		Mo(d, n) (SL4)
44 Ru	95	F			20 m (D7)		Ru(n, 2n(?)) (D7, P2)
Ru	97	B	K, e <sup>-</sup> , $\gamma$		2.8 d		0.23 (P46)
Ru	103	A	$\beta$ -, $\gamma$		45 d (P47)	0.2, 0.8 d (P47) abs A1	0.56 (P47) abs Pb fiss (P47)



Isotope Z El	A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Ru 105	A		$\beta^-$ , $\gamma$	4 h (D7, L13, NL2) 4.5 h (P47)	1.5 (B31) abs Al 1.35 (P47) abs Al	0.76 (P47) abs Pb	Ru(n, $\gamma$ ) (D7) Ru(d, p) (L13) fiss(S33, NL2, NL3, P47)
Ru 106	A		$\beta^-$	330 d (P46)	0.2 (P46)	No $\gamma$	Th(n) (S33) Ru(d, ?) (L13) fiss(P47)
Ru 107	E			60 d (P46)		No $\gamma$	fiss(NL2, NL5)
Ru 110	E			90 m (K3)			Mo( $\alpha$ , n) (K3)
Ru 111	D		$\beta^-$	4 m (B31)	4 (B31) abs		fiss(B31)
45 Rh 102	A		$\beta^-$ , $\beta^+$ , $\gamma$ (M23)	210 d (M23)	1.1 ( ) (M23) abs		Rh(n, 2n) (M23)
Rh 103	A		I.T.e $^-$ (W56)	45 m (W56) 48 m (P47) 56 m (P47)	e $^-$ : 0.03 (P47) abs Al	0.04, 1.22, 1.60, 1.96, 2.33, 2.67, 3.01 (W56) 0.019 (P46)	Rh(X-ray) (W56) Rh(n, n) (P47) fiss(P47)
Rh 104	A		I.T.e $^-$ (P5)	4.2 m (P5)		0.055-0.080 (P5) abs of e $^-$ ; 0.069 (09) spect conv	Rh(n, $\gamma$ ) (P5, Al, P2) Ru(p, n) (D9)
Rh 104	A		$\beta^-$	44 s (P5, Al)	2.3 (Cl3) cl ch		Rh(n, $\gamma$ ) (P5, Al) Rh <sup>104</sup> (4.2 m) I.T. (P5) Ru(p, n) (L13)
Rh 105	A		$\beta^-$ , $\gamma$	34 h (NL2, NL3) 36.5 h (P47)	0.5 (NL3) abs Al 0.6 (P46)	0.33 (P47) abs Pb	Ru <sup>105</sup> $\beta$ -decay (NL2, D7, L13) fiss(P47)
Rh 106	A		$\beta^-$ , $\gamma$	30 s (P46)	4.5 (P47) abs 2.8 (P47) abs	0.3, 0.8 (P47) abs Pb	fiss(P47) Ru(p, n(?) ) (D9)
Rh 107	C		$\beta^-$	24 m (B31)	1.2 (B31) abs Al		Ru(4min) $\beta$ -decay (B31) fiss(P47)

Isotope Z El	A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Rh 109	A	$\beta^-$		1 h (P46)			Ru(p,n(?))(D9)
Rh 110	D	$\beta^-$ , $\gamma$		9 m (P46)			Ru(p,n(?))(D9)
Rh 111	D	$\beta^-$		24 m (P46)	1.2 (P46)		
46 Pd 103	A	K		17.0 d (P46)			
Pd 107	A	$\beta^-$					fiss (P47)
Pd 109	A	$\beta^-$		13.4 h (P47) 13 h (K6)	1.1 (P47) abs Al 1.03 (P47, K6) cl ch 1.1 (P46)	No $\gamma$	Ag109(H <sup>3</sup> , He <sup>3</sup> )(K50) fiss (P47) Pd(d,f)(K6) Pd(n, $\gamma$ )(Al, K6) Ag(n,p)(F5)
Pd 111	A	$\beta^-$		26 m (S33)	3.5 (B31) abs		Pd(d,f)(K6, Al) Pd(n, $\gamma$ )(K6, Al) fiss (S33, NL4)
Pd 112	A	$\beta^-$		17 h (S33, NL4) 21 h (P47)	0.2 (P47)	No $\gamma$	fiss (S33, NL4)
47 Ag 102	E			73 m (E6)			Pd(p,n)(E6)
Ag 104	E			16.3 m (E6)			Pd(p,n)(E6)
Ag 105	E	K, $\gamma$		45 d (E6)		0.29, 0.42, 0.50, 0.62 (E6) spect; 0.82, 0.345, 0.430, 0.650, > 1.0 (D19) spect	Pd(p,n)(E6)



Isotope Z El	A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Ag 106	A	$\beta^+$		24.5 m (P6, D2)	2.04 (F5) abs	No $\gamma$ (F5)	Ag(n, 2n) (P6) Pd(d, n) (F6) Cd(n, p) (P6) Rh( $\alpha$ , n) (P6, K3) Ag( $\gamma$ , n) (B20) Pd(p, $\gamma$ ) (D2) Pd(p, n) (D2, E6) Ag(d, p, 2n) (K15, K31)
Ag 106	A	K, $e^-$ , $\gamma$ (H50, P6, F5, A4)		8.2 d (P6, K6)	1.2 ( $e^-$ ) (F5) abs	1.06, 0.69 (E6) spect; 1.63, 1.06, 0.72 (?) (D19) spect	Ag(n, 2n) (P6, K6) Pd(d, n) (P6, K6) Rh( $\alpha$ , n) (P6) Pd(p, n) (D2, E6) Cd(n, p) (P6) Ag(d, f, 2n (?)) (K23)
Ag 107	A	I. T., $e^-$		40 s (A12) 44 s (P46)		0.093 (V7, A12, H9) spect conv	Cd <sup>107</sup> , 109 (6.7 h) K decay (A12, H34) Cd <sup>107</sup> , 109 (158 d) K decay (H34) Ag(n, n) (A12) Pd <sup>107</sup> , 109 $\beta$ -decay (S33) Ag(X-rays) (F9)
Ag 108	A	$\beta^-$		2.3 m (A1, B20)	2.8 (N4) cl ch		Ag(n, $\gamma$ ) (A1) Ag( $\gamma$ , n) (B20) Pd(p, n) (D2, E6) Cd(n, p) (P6) Ag(d, p) (K12, K15)
Ag 109	A	$e^-$ , I. T., $\gamma$ (P47)		40.4 s (P47)	$e^-$ : 0.0662, 0.0896, 0.915 (F47) spect	0.087, 1.09, 2.23, 2.67, 3.04 (W56)	Ag(X-ray) (W56) fiss (P47)
Ag 110	A	$\beta^-$ , $\gamma$ (P6)		22 s (A1, P6)	2.8 (G4) cl ch (K.U.)		Ag(n, $\gamma$ ) (A1) Cd(n, p) (P6)

Isotope Z El	A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced By
					Particles	Gamma Rays	
Ag 110	A		K, $\gamma$ , e <sup>-</sup> (K15, H59)	225 d (LL4, R10)	0.58 (P46)	0.650, 0.925, 1.51, (D19) spect; 0.6 (K15) abs Al	Ag(n, $\gamma$ ) (R10, LL4, A8, WL2) Ag(d, p) (K12, K15, H59)
Ag 111	A		$\beta^-$	7.5 d (K6, P6)	$\sim$ 0.8 (B30) abs Al; 0.24 (P47) abs Al.	No $\gamma$ (K6, P6)	Pd(d, n) (K6, P6) Pd( $\alpha$ , p) (P6) Cd(n, p) (P6) Pd111 decay (K6, S33, NL4) fiss (P47)
Ag 112	A		$\beta^-$ , $\gamma$	3.2 h (P6)	2.2 (P6) cl ch 3.6 (P47) abs Al	0.86 (P47) abs Pb	Cd(n, p) (P6) In(n, $\alpha$ ) (P6) fiss (N9, P47) Pd112 $\beta$ -decay (S33, NL4)
48 Cd 105	D		$\beta^+$	33 m (P46)			
Cd 107	A		$\beta^+$ , K, $\gamma$ (D4, V7, WL1, A12, B73)	6.7 h (D4, R5)	0.32 ( ) (B73)	0.51 (anti $\mu$ ) (V7) 0.842 (B73)	Ag(p, n) (D4, R5, V7, WL1) Ag(d, 2n) (K12, A12, H34, K15)
Cd 109	C		K	330 d (P46)			Ag(d, 2n) (H34, K15)
Cd 111	D		I. T., e <sup>-</sup>	48.7 m (W30)		0.155 (W30)	Cd(n, n) (D8) fiss (N9, N14) Cd(x-ray) (F9, W30) Cd(e <sup>-</sup> , e <sup>-</sup> ) (W30)
Cd 115	A		$\gamma$ $\beta^-$	43 d (S79) 40 d (P47)	1.5 (S79) abs 1.7; 1.8 (P47) abs Al	0.5 (S79) abs Pb	In115(n, p) (S79) Cd(d, p) (C14) fiss (P47)



Isotope		Type of Class Radiation	Half-life	Energy of Radiation in mev		Produced By
Z	EI A			Particles	Gamma Rays	
Cd	115	A $\beta^-$ , $\gamma$	2.5 d(G5) 2.33 d(P47)	1.11(C14)spect 0.56, 1.20(P47)abs A1	0.55(L57)c1 ch recoil; 0.65(M34) spect	Cd(d,p)(C14) Cd(n, $\gamma$ )(G5, M10) Cd(n,2n)(G5) fiss(N9, N14)
Cd	117	A $\beta^-$	2.83 h(P46) 2.72 h(P46)	1.3-1.7(P47)spect	No $\gamma$	Cd(d,p)(C14) Cd(n, $\gamma$ )(M10, G5) fiss(N9, N14)
Cd		C I.T.e $^-$	48.7 m(W30) 50 m(P47)	e $^-$ : 0.17(P47)abs A1	0.195(W30)abs of e $^-$	Cd(n,n)(D8) fiss(N9, N14) Cd(x-ray)(F9, W30) Cd(e $^-$ , e $^-$ )(W30)
49 In	110	D $\beta^+$	65 m(B17)	1.6(B17)spect		Cd(p,n)(B17) Ag( $\alpha$ ,n)(K9) Cd(d,2n)(L57)
In	111	D $\beta^+$ , $\gamma$ , e $^-$	20 m(B17)	1.7( $\beta^+$ )(L57)c1 ch	0.16(B17)spect conv	Cd(d,n)(L57) Cd(p,n)(B17)
In	111	A K, $\gamma$ , e $^-$ (L57)	2.7 d(B17, C14)		0.17, 0.25(B17, C14) spect conv	Cd(p,n)(B17) In(n,2n)(C14) Cd(d,n)(L57) Ag( $\alpha$ ,n)(L57)
In	112	D I.T., $\gamma$ , e $^-$	16.5 m(S34)		0.120(S34)abs of e $^-$	Ag( $\alpha$ ,n)(S34) In(n,2n)(S34)
In	112	D $\beta^+$ , $\gamma$ , e $^-$ (S34)	17.5 m(S34)	1.3( $\beta^+$ )(S34)abs; 0.47 ( $\beta^+$ , $\gamma$ )(S34)abs	0.095(S34)abs of e $^-$	Ag( $\alpha$ ,n)(S34) In(n,2n)(S34) In112(16.5 m)I.T. (S34)

Isotope Z El A	Type of Class Radiation	Half-life	Energy of Radiation in mev		Produced By
			Particles	Gamma Rays	
In 113	A I.T., $\gamma$ , $e^-$ (B17)	105 m (B17)		0.39 (B17, L57) spect conv	Cd(p, n) (B17) Sn <sup>113</sup> decay (B17, S22) Cd(d, n) (L57)
In 114	A I.T., $e^-$ (L57, L48)	48 d (B17)		0.19 (B17, L57) spect conv	In(n, $\gamma$ ) (L15, M12) Cd(p, n) (B17) In(d, p) (L57) Cd(d, n) (L57) In(n, 2n) (L57)
In 114	A $\beta^-$	72 s (L15, B17)	1.98 (L32) cl ch		In <sup>114</sup> (48 d) i. t. (L48, L57) In(n, 2n) (L15, P2) In( $\gamma$ , n) (B11, C5) Cd(p, n) (B17)
In 115	A I.T., $e^-$ , $\gamma$ (L57, W56)	4.42 h (G5, B18, W56); 4.5, 4.3 4.1 h (P47)	$e^-$ : 0.308, 0.332 (P47)	0.34, 0.78, 1.21, 1.79, 2.29 (O57, W56)	In(n, n) (G5) In(p, p) (B18) In( $\alpha$ , $\alpha$ ) (L16) In(x-ray) (P7, C10, W56) Cd <sup>115</sup> $\beta$ -decay (G5) Cd(d, n) (L57) fiss (NL4, P47)
In 116	A $\beta^-$	13 s (A1, CL4)	2.8 (CL4) cl ch	Not (M11)	In(n, $\gamma$ ) (A1, L15) In(d, p) (L15) Cd(p, n) (D9)
In 116	A $\beta$ , $\gamma$	54 m (A1, L15)	0.85 (CL4, C44) spect cl ch	1.8, 1.4, 1.0, 0.6, 0.4, 0.2 (C44) cl ch recoil; 2.32, 1.31, 1.12, 0.428 (D19) spect	In(n, $\gamma$ ) (A1, M11) Cd(p, n) (B17) In(d, p) (L15)
In 117	A $\beta^-$ , $e^-$	117 m (L32)	1.73 ( $\beta^-$ ) (CL4) spect 1.9 (P46)		Cd <sup>117</sup> $\beta^-$ -decay (G5) Cd(d, n) (CL4, L57) fiss (NL4)



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
50 Sn 113	A	K, e <sup>-</sup> , γ	70-105 d (L17, B17)		0.085 (B17) spect conv	In(p,n)(B17) Sn(d,p)(L17) Cd(α,n)(L17)
Sn < 119	E	β-	25 m (L17)			Cd(α,n)(L17)
Sn < 119	E	β-	3 h (L17)			Cd(α,n)(L17)
Sn < 119	E	β-	13 d (L17)			Cd(α,n)(L17)
Sn 121	C	β-	~80 h (H55); ~60 h (N15, P47)	0.76 (P47) abs Al		Fiss (H55, N15, P47)
Sn 123	C	β-	10 d (L17)	0.26 (P47) abs Al		Sn(d,p)(L17) Sn(n,γ)(L17) Fiss (P47)
Sn 125	B	β-	9 m (L17)			Sn(d,p)(L17) Sn(n,γ)(L17) Fiss (P47)
Sn > 125	D	β-	~20 m (H55)			Fiss (H55, P47)
Sn > 125	D	β-	~11 d (H55)			Fiss (H55)
Sn > 125	F	β-	~4-5 d (H55)			Fiss (H55)
Sn < 126	D	β-	40 m (L17)			Sn(d,p)(L17) Sn(n,γ)(L17) Sn(n,2n)(P2)
Sn < 126	D	β-	26 h (L17)			Sn(d,p)(L17) Sn(n,γ)(L17)
Sn < 126	D		~400 d (L17)			Sn(d,p)(L17)
Sn > 126	C	β-, γ(?)	~70 m (N15, H55)	0.7, 2.7 (P47) abs Al	1.2 (P47) abs Pb	Fiss (N15, P47, H55)

Isotope Z El A	Class	Type of Rad- iation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
51 Sb	E	$\beta^-$	3.5 m(D9)			Sn(p,n)(D9)
Sb 118	B	$\beta^-$	3.6 m(R16)			In( $\alpha$ ,n)(L16,R16)
Sb 120	A	$\beta^+$	17 m(H10,L18)	1.53(A10) elcoh		Sb(n,2n)(P2,H10) Sb( $\gamma$ ,n)(B20) Sn(d,n)(L18) Sn(p,n)(D9) Sb(d,H <sup>3</sup> )(K14)
Sb 122	A	$\beta^-, \gamma$	2.8 d(L28)	0.81, 1.64 (A10,M35) cl ch abs	0.96(M35)coin- cid abs; 0.80 (M34) spect	Sb(d,p)(L18) Sb(n, $\gamma$ )(A1,L18) Sn(d,2n)(L18) Sn(p,n)(D9)
Sb 124	A	$\beta^-, \gamma$	60 d(L18)	1.53(M35)abs 0.74, 2.45(H35, H49) spect	1.82(M35)coin- cid abs; 1.75 (K16) Be(r,n) reaction	Sb(d,p)(L18) Sb(n, $\gamma$ )(L18) I(n, $\gamma$ )(L18)
Sb 125	B	$\beta^-, \gamma$	2.7 y(L18) P47)	0.3, 0.7, 0.6 (P47)abs Al	0.6, 0.027(P47) abs Pb	Sn(d,n)(L18) Fiss(P47)
Sb 126	C	$\beta^-, \gamma(?)$	60 m(N15)			Sn <sup>125</sup> (70 m) $\beta^-$ - decay (N15) Fiss (P47)
Sb 126	D	$\beta^-$	3 h (L18)			Sn(d,n)(L18)
Sb 126	D		$\sim 45$ d(L18)			Sn(d,n)(L18)
Sb 127	A	$\beta^-$	80 h(A6)	1.15(P47) abs Al	0.72(P47) abs Al	Fiss (A6)



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev Particles	Gamma Rays	Produced by
51 Sb 129	A	$\beta^-$	4.2 h (A6)			Fiss (A6)
Sb 131	D	$\beta^-$	<10 m (A6)			Fiss (A6)
Sb 132	B	$\beta^-$	5 m (A6)			Fiss (A6)
Sb 133	A	$\beta^-$	<10 m (A6) W21)			Fiss(A6, S21, W21) Fiss(S21, W21)
Sb 134	D	$\beta^-$	<10 m (P47)			Fiss(P47)hyp
52 Te 121	A	K, $e^-$ (S15, 08)I.T.	125 d (S15) 143 d (P45)	0.61, 0.223 (Y3, P45) coin- cid		Sb(d, 2n)(S15, P45) Sn( $\alpha$ , n)(S15) Sb(p, n)(S15, P45)
Te 121	A	K, $\gamma$	17 d (P45)	0.61 (P45)		Sb(d, 2n)(S15, P45) Sb(p, n)(S15, P45)
Te 122	E	I.T., $e^-$ (?)	30 d (K17)	e: 0.0820, 0.0883, 0.136, 0.1573, 0.2108, 0.615 (K17) spect conv		Sb(d, n)(? (K17)

Isotope Z El A	Class	Type of Radiation	Energy of Radiation in mev		Produced by
			Half-life	Particles	
52 Te 127	A	I.T., $e^-$ (S15)	90 d(S15)	$e^-$ : 0.055, 0.082, 0.085 (P47) spect	Te(d,p)(S15) I(n,p)(S15) Fiss(P47)
Te 127	A	$\beta^-$	9.3 h(S15)	0.7(P47)abs Al	Te(d,p)(S15) T4 I(n,p)(S15) Te(n,2n)(T4) Te 127 (90 d) I.T.(S15) Sb 127 $\beta^-$ -decay(A6) Fiss(P47)
Te 129	A	I.T., $e^-$ (S15)	32 d(S15)	$e^-$ : 0.07, 0.1 (P47) spect	Te(d,p)(S15,T4) Te(n,2n)(T4) Fiss(H55,P47)
Te 129	A	$\beta^-$ , $\gamma$	72 m(S15,A6) 70 m(P47)	1.8(P47)spect, 1.75(P47)abs Al	Te(d,p)(S15,T4) Te( $\gamma$ ,n)(B20) Te(n,2n(H10),T4) Te 129(32 d)I.T. (S15) Sb 129 $\beta^-$ -decay (A6) Fiss(P47)
Te 131	A	I.T., $e^-$ (S15)	30 h(S15,A6)	0.147, 0.175 (P47) spect	Te(d,p)(S15) Fiss(A6,H22) (P47)



Isotope Z el A	Class	Type of Radiation	Energy of Radiation in mev		Produced by
			Half-life	Particles	
52 Te 131	A	$\beta^-$	25 m (S15) 30 m (P47)		Te(d,p)(S15) Te(n, $\gamma$ )(S15) Fiss(A6,P47) Te 131(30 h) I.T.(S15)
Te> 131	A	I.T., $e^-$	77 h (A6) 30 h (P46)	$\sim 0.3$ (B30) abs	Sb>131(5 m) $\beta^-$ -decay(A6, H22) Fiss(H24)
Te 132	B	$\beta^-$ , $\gamma$	77 h	0.28 (P47) abs A1	Fiss(P47)
Te 133	A	$\beta^-$	60 m (A6, W21)	0.22 (P46) abs Pb	Sb 133 $\beta^-$ de- cay(A6, H22, S21, W21)
Te 134	C	$\beta^-$	43 m (A6)		Sb 131(<10 m) $\beta^-$ -decay(A6, H22) Fiss(P12)
Te 135	A	$\beta^-$	<1 m-15 m (W21, S21)		Fiss(S21, W21) (P47)
Te 136	D	$\beta^-$	$\sim 1$ m (H55)		Fiss(H55, P47)
53 I 124	A	$\beta^+$	4.0 d (L19, D9)	$\sim 0.1$ (P46)	Sb( $\alpha$ ,n)(L19) Te(p,n)(D9)
I 125	D	K	56 d (P46)		

Isotope Z El A	Class	Type of Radia- tion	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
53 I 126	A	$\beta^-$ , $\gamma$	13.0 d(L19, T4)	1.1(L19)abs	0.5(L19)abs Pb	Sb( $\alpha$ ,n)(L19) I(n,2n)T4,L1 Te(d,n)(L19) Te(p,n)(D9)
I 128	A	$\beta^-$ , $\gamma$	24.99 m(H36)	1.85(B14)cl ch or 1.05, 2.10(B14) cl ch (K.U.) 1.59, 7%(S85) 2.02, 93%(S85)	0.4(L19)abs Pb; 0.428 (S85)spec(L19) abs Pb	I(n, $\gamma$ )(A1,T4, S85) Te(d,2n)(L19) Te(p,n)(D9)
I 130	A	$\beta^-$ , $\gamma$	12.6 h(L19)	0.61, 1.03(R23) spect, coincid	0.417, 0.537, 0.667, 0.744 (R23)spect conv, spect coincid	Te(d,2n)(L19) Te(p,n)(D9) Cs(n, $\alpha$ )(W21) Fiss(P15)
I 131	A	$\beta^-$ , $\gamma$	8.0 d(L19) 7.9 d(P47)	0.687(T7)cl ch; 0.595(D29,D30, D31)spect coin- cid	0.4(L19)abs Pb; 0.367, 0.080(D30; D31)spect, spect,conv coincid	Te(d,n)(L19, R19) Te 131 $\beta^-$ de- cay(S15, A6,H22) U( $\alpha$ )(F10) Fiss(P47)
I 132	B	$\beta^-$ , $\gamma$	2.4 h(A6) 2.3 h(P47)	$\sim$ 1.35(B30)abs 1.0, 2.1(P47) abs Al	0.85(B30)abs 0.6, 1.4(P47) abs Pb	Te 131(77 h) $\beta^-$ decay(A6 H22,P12) U( $\alpha$ )(F10) Fiss(P47)
I 133	A	$\beta^-$ , $\gamma$	22 h(A6,W21) 18.5 h(P47)	1.1(P13)cl ch 1.3(P47)abs Al	0.55(P47)abs Pb	Te 133 $\beta^-$ decay (H22,A6, S21,W21) U( $\alpha$ )(F10) Fiss(P47)



Isotope Z El A	Class	Type of Radiation	Energy of Radiation in mev		Produced by
			Half-life	Particles	
53 I 134	C	$\beta^-$	54 m(A6)	$\approx 1$ : (P47)abs Al	Te 134(43 m) $\beta^-$ decay(H22,A6, P12,P15) Fiss(D6)(P47) U( $\alpha$ )(F10) Fiss(P47)
I 135	A	$\beta^-$ , $\gamma$	6.6 h(S21,D27, W21)	1.35, 1.5(P47)abs Al	Te 135 $\beta^-$ decay(S2, W21) Fiss(P47)
I 136	C	$\beta^-$	1.8 m(S35)		Fiss(S35, P47)
I 137	B	$\beta^-$	30 s(S35)22.5 s	2.1(P46)	Fiss(S35, S43, P47)
I 137	C	$\beta^-$ ; ( $\alpha$ ) (P47)	22. s 23. s(P47)		Fiss(P47)
54 Xe 127	B	I.T.( $\gamma$ ), $e^-$ , $\gamma$ (C41)	75 s(C41)	0.175, 0.125 (C41)spect conv	I(p,n)(B41, C41)
Xe 127	B	$e^-$ , $\gamma$ (C41)	34 d(C41)	0.9(C41)abs of $e^-$	I(p,n)(C41)
Xe 133	A	$\beta^-$ (S47) $\gamma$ , $e^-$	7.0 d(R22); 5.4 d(C22); 5.3 d(P47)	0.2-0.3(B30, S47)abs; 0.32, 0.33, 0.35(P47)abs Al $e^-$ : 0.049(P47) spect	I 133 $\beta^-$ decay(S21, D27, W21) Xe(d,p)(C22) Te( $\alpha$ ,n)(C22) Xe(n, $\gamma$ )(R22) Cs(n,p)(W21) Ba(n, $\alpha$ )(W21, S47) Fiss(P47)

Isotope Z El	Class A	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
54 Xe 135	A	$\beta^-$ , $\gamma$ (B30)	9.4 h(S21,W21) 9.2 h(P47)	0.95(B30)abs Al; 0.9(S47)abs Al	0.25(P47)abs Al	I 135 $\beta^-$ decay(S21 (D27,W21) Xe(d,p)(C22) Ba(n, $\alpha$ )(W21,S47) Fiss(P47)
Xe 135	A	I.T., $\gamma$ (B30) $e^-$ , (P47)	15.6 m(R22) 13 m(P47) 10 m(P47)	$e^-$ : 0.7(B30)abs Al; 0.6(S47)abs Al	0.54, 0.60(P47) abs Al	IL35 $\beta^-$ decay (G11) Xe(n, $\gamma$ )(R22) Fiss(P47)
Xe 137	A		68 m(C22)			Xe(d,p)(C22)
Xe 137	D	$\beta^-$	3.4 m(R22) 3.8 m(P47)	4(B30)abs Al		I 137 $\beta^-$ decay (S43) Xe(n, $\gamma$ )(R22) Fiss(P47)
Xe 138	B	$\beta^-$	17 m(G21)	1.1(P46)		Fiss(H28,H22,G9, G21,S47,P47)
Xe 139	A	$\beta^-$	<0.5 m(H28) 41 s(P46)	2.1(P46)		Fiss(H28,H22, H11,P47) Fiss(H29,A5,P47)
Xe 140	A	$\beta^-$	<0.5 m(H28)			Fiss(H28,P47,H29)
Xe 141	A	$\beta^-$	16 s(P46) 1.7 s(P46)			
Xe 143	A	$\beta^-$	1 s(P46)			
Xe 144	D	$\beta^-$	0.5 s(P47)			
Xe 144	A	$\beta^-$	Short			



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
55 Cs 130	B		30 m (P46)			
Cs 131	D	$K, \gamma, e^-$	10 d (P46)			
Cs 132	B	$K, T, e^-$	7.1 d (P46)		0.145 (P46)	
Cs 134	A	$\beta^-(K26)$ $\gamma(P46)$	3 h (K26)	1 (K26) abs	0.7 (P46)	Cs (n, $\gamma$ ) (A1, M16, K26) Cs (d, p) (K26)
Cs 134	A	$\beta^-, \gamma(K26)$	1.7 y (K26)	0.9 (K26) abs 0.645 (S78)	0.776, 1.35, 0.584, (S78)	Cs (n, $\gamma$ ) (A8, S20, K26) Cs (d, p) (K26)
Cs 136	A	$K, \beta^-, \gamma, e^-$	10.5 d (P46)	$\sim 0.2$ (P46)		Fiss (P47)
Cs 137	A	$\beta^-, \gamma$	33 y (P47)	0.8, 0.5 (P47) abs Al	0.75 (P47) abs Pb	Fiss (P47)
Cs 138	B	$\beta^-, \gamma$	33 m (H28)	2.6 (G21) abs	1.2 (P47)	Xe 138 $\beta^-$ decay (H28, H22, G9, G21) Pa (n) (G7) Ba (n, p) (S47) Fiss (P47)
Cs 139	A	$\beta^-$	7 m (H28) 10 m (P47)			Xe 139 $\beta^-$ de- cay (H28, H22, H11) Fiss (P47)
Cs 140	C	$\beta^-$	40 s (H28)			Xe 140 $\beta^-$ de- cay (H28)
Cs 141	A	$\beta^-$	Short			

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
55 Cs 142	D	$\beta^-$	1-2m			
Cs 143	A	$\beta^-$	Short			
Cs 144	A	$\beta^-$	Short			
Cs 145	C	$\beta^-$	Short			
56 Ba 131	D	K, $\gamma$	11.7 d (P46)		0.2, 0.5 (P46)	
Ba 133	A	I.T., $e^-, \gamma$ (C30)	38.8 h (W28)		0.30 (D9) spect conv; 0.276 (C30) spect conv	Ba(n,2n)(K26, W22) Cs(p,n)(D9, W28) Cs(d,2n)(C30, W28) Ba(d,p)(W22)
Ba 139	A	$\beta^-, \gamma$	86 m (P8, H28) 85 m (P47) 87 m (P47)	1 (K26) abs; 2.3 (B30) abs	0.6 (K26) abs Pb Cu	Ba(d,p)(P8, K26) Ba(n, $\gamma$ )(A1, P2) La(n,p)(P8) Cs 139 $\beta^-$ -de- cay (H29, H22 H11) U( $\gamma$ )(L2) Ce(n, $\alpha$ )(W22) Fiss (P47)
Ba 139	D		3 m (A1, P2)			Ba(n,?)(A1, P2, K26)
Ba 140	A	$\beta^-, \gamma$	$\sim$ 300 h (H28, G21); 12.8 d (P47)	1.2 (B30) abs 1.05 (P47) spect 0.4, 1.0 (P47) abs Al	0.542 (P47) 0.529 (P47)	Cs 140 $\beta^-$ -de- cay (G21) Fiss (P47)



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
56 Ba 141	A	$\beta^-$ , $\gamma$	18 m (H48)			Fiss (H48, P47) Fiss (H15, H14, P47) Fiss (L2, P47)
Ba 142	B	$\beta^-$	6 m (H48)			Fiss (H48, P47) Fiss (H15, H14, P47) Fiss (L2, P47)
Ba 143	A	$\beta^-$	<1 m (H14)			Fiss (H14, P47)
Ba 144	A	$\beta^-$	<0.5 m (P47)			Fiss (P47)
57 La 137	B	K, $\gamma$ (W23, M24)	17.5 h (W23)		0.88 (W23) abs Pb	Ba (d, n) (W23, M24) Ba (p, n) (W23, W22)
La 138	F		2.2 h (P2)			La (n, 2n) (?) (P2)
La 140	A	$\beta^-$ , $\gamma$	40.0 h (W23)	0.9, 1.41 (W23) abs Al, spect; 1.41, 1.5, 1.75 (P47) abs Al	2.00 (W23, M24) abs Pb; 2.04 (M27) spect; 0.335, 0.49, 0.87, 1.65 (P47) spect, 0.333, 0.505, 0.832, 1.61, 2.52 (P47) spect	La (d, p) (P8, W23, M24) La (n, $\gamma$ ) (P9, M13, W23, M24, G14) Ce (n, p) (W23) Ba (d, $\gamma$ ) (?) (W23) Ba 140 $\beta^-$ decay (H48, H28, H22, G21) Fiss (P47)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
57 La 141	A	$\beta^-$ ( $\gamma$ ?)	3.5 h (H48) 3.7 h (P47)	2.8 (P47)	No $\gamma$	Ba 141 (18 m) $\beta^-$ -decay(H48) Fiss(C16)
La 142	C	$\beta^-$ , $\gamma$	74 m(H48)			Ba 142 (6 m) $\beta^-$ -decay(H48) Fiss(P47)
La 143	A	$\beta^-$	20 m(H14,H15, P47) 19 m(P47)			Ba 143 (<1 m) $\beta^-$ -decay(H14, H15) Fiss(P47)
La >140	F	$\beta^-$	15 m(H55)			Fiss(H55)
La >140	F	$\beta^-$	13 d(H55)			Fiss(H55)?
58 Ce 139	F	$\beta^+$	2.1 m(P9)			Ce(n,2n)(?)(P9)
Ce 140	B	I.T., $\gamma$ (P14)	140 d(P14)		0.21(P14)	La(d,n)(P14) Ba(a,n)(P14)
Ce 141	A	$\beta^-$ , $\gamma$	30 d(P14)	0.65(P14) 0.55(P47) abs Al	0.2(P14) 0.22, 0.21 (P47)abs Pb	Ce(d,p)(P14) Ce(n, $\gamma$ )(P14) Ce(n,2n)(P14) Ba(a,n)(P14) Pr(n,p)(P14) Fiss(P47)
Ce 143	A		15 d(R11)	0.12(R11)spect		Ce(n, $\gamma$ )(R11)
Ce 143	B	$\beta^-$ , $\gamma$	33 h(P47) 36 h(P14)	1.35(P47)abs Al	0.5(P47)abs Pb	Ce(d,p)(P14) Ce(n, $\gamma$ )(P14)
Ce 144	A	$\beta^-$	310 d(B30, H55); 275 d(P47)	0.348(P47)abs Al	No $\gamma$	Fiss(Xe parent) (B30,H55,P47)



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
58 Ce 145 C	C	$\beta^-$	1.8 h(P47)			Fiss(Xe parent) (H55, P47)
Ce 146 C	C	$\beta^-$	$\sim 15$ m(G19) $< 14.6$ m(P46)			Fiss(H55, G19, P47)
Ce	D	$\beta^-$	$\sim 4-5$ h(H55)			Fiss(H55, P47)
Ce	D	$\beta^-$	$\sim 40$ hr(H55)			Fiss(H55, P47)
59 Pr 140 A	A	$\beta^+$	3.5 m(P9)	2.40(D32)ol ch		Pr(n,2n)(P9, Al, W25, D32)
Pr 142 A	A	$\beta^-, \gamma$	19.3 h(D32)	2.14(D32)spect	1.9(D32)abs Pb	Pr(n, $\gamma$ )(P9, P2, M13, Al, W25, D32) Nd(n, p)(P9, P2) Pr(d, p)(D32) Ce(p, n)(D32) La( $\alpha$ , n)(D32)
Pr 143 A	A	$\beta^-$	13.5 d(P14) 14. d(P47)	0.95(P14), 1.0 (P47)		Ce 143 $\beta^-$ decay (P14) Fiss(H55, P47)
Pr 144 A	A	$\beta^-, \gamma, e^-$	17 m(H55) 18 m(P47)	3.1(B30, H55)abs Al	0.135, 0.145 (P47)abs Pb	Ce (310 d) $\beta^-$ decay(H55) Fiss(P47)
Pr 145 C	C	$\beta^-$	4.5 h(P46)	3.1(P47)abs Al	No $\gamma$	Fiss(P47)
Pr 146 C	C	$\beta^-, \gamma$	25 m(G19) 24.6 m(P47)	$\sim 3$ (P47)abs Al	1.4(P47)abs Pb	Ce ( $\sim 15$ m) $\beta^-$ decay(G19)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particules	Gamma Rays	
60 Nd	141 A	$\beta^+$	2.5 h (K19)	0.78 (K19)		Nd(d, H <sup>3</sup> )(?)(P9, K19) Nd(n, 2n)(P9, K19 L25) Pr(p, n)(K19) Nd( $\gamma$ , n)(L25, K19)
Nd	147 A	$\beta^-$ , $\gamma$ , e <sup>-</sup>	11.0 d (P47)	0.95 (W25) abs 0.4 (P47)	0.58 (P47) abs Pb	Nd(d, p)(P9, L25) Nd(n, $\gamma$ )(P9, L25, W25) Nd(n, 2n)(?)(P9) Fiss(P47)
Nd	149 C	$\beta^-$ , $\gamma$	1.7 h (P47) 2.0 h (P47)	1.5 (P47)		Fiss(P47)
Nd	151 D	$\beta^-$	21 min (P9) Short (P46)			Nd(n, $\gamma$ )(P9, M18) Fiss(P47)
61 61	143 E	$\beta^-$	12.5 h (P9)			Nd(d, n)(P9)
61	144 E	K or I.T., $\gamma$ (W25)	$\sim$ 200 d (W25)		0.67 (W25) abs	Pr( $\alpha$ , n)(W25, K21) Nd(d, n)(K20, K21)
61	145 E	$\beta^-$ , $\gamma$	2.7 h (K20)	2 (K20)		Nd(p, n)(K20, L25) Nd(d, n)(K20, L25) Nd( $\alpha$ , p)(L25)
61	146 E	$\beta^-$ , $\gamma$	16 d (K20)	1.7 (K20)		Nd(d, n)(K20)
61	147 A	$\beta^-$	4 y (P47) 3.7 y	0.2 (P47) abs Al	No $\gamma$	Fiss(P47)
61	148 B	$\beta^-$ , $\gamma$	5.3 d (K20)	2 (K20)		Nd(p, n)(K20) Nd(d, n)(K20, K21, L25) Nd( $\alpha$ , p)(K21, L25)



Isotope		Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
Z	El A				Particles	Gamma Rays	
61	61	149	B	$\beta^-$ , $\gamma$	47 h (P47)	1.1 (P47) abs Al	0.25 (P47) ab Al Fiss (P47)
61	61	151	D	$\beta^-$	12 m (P47)		Fiss (P47)
62	Sm	148 (W40)	A	$\alpha$ (1185, 174)	1.4 x 10 <sup>11</sup> y (1186); 1.7 x 10 <sup>11</sup> y (W40)	2.0 (H86) cl ch	Natural source (H85, L74)
Sm	153	A	I.T. (W25) $\beta^-$ , $\gamma$ (P47)	46 h (P9, P47)	0.73, 0.70 (P47) abs Al	0.6 (M31) abs of $e^-$ 0.11, 0.57 (P47) abs Al; 0.11, 0.6 (P47) spect	Sm (n, $\gamma$ ) (P9, H20, R11, H17, W25) L25 Sm (n, 2n) (?) (P9, K19) Sm (d, p) (L25, K19) Sm ( $\gamma$ , n) (L25) Nd ( $\alpha$ , n) (K19) Fiss (P47)
Sm	155	B	$\beta^-$ , $\gamma$	21 m (P9) 25 m (P47)	1.8 (K19) abs Al 1.9 (P47) abs Al	0.3 (P47) abs Al	Sm (n, $\gamma$ ) P9, Al, M13 H17, L25 Sm (n, 2n) (?) (P9, K19) Sm ( $\gamma$ , n) (L25) Sm (d, p) (L25, K19) Nd ( $\alpha$ , n) (K19) Fiss (P47)
Sm	156	A	$\beta^-$	10 h (P47)	0.8 (P47) abs Al		Sm (d, p) (K19, L25) Sm (n, $\gamma$ ) (K19) Nd ( $\alpha$ , n) (K19) Fiss (P47)
63	Eu	150	E $\beta^+$	27 h (P9)			Bu (n, 2n) (?) (P9, R11)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
63 Eu 152	A	$\beta^-$ , $\gamma$ , $e^-$ (T6); $K(\gamma)$ (R2)	9.2 h (P9)	1.88( $\beta^-$ )(T6) spect	0.123, 0.163, 0.725 (T6)spect conv	Eu(n, $\gamma$ )(P9, M13, H17, H20, F11) Eu(n, 2n)(?)(P9) Eu(d, p)(F4, F11)
Eu 154	A	$\beta^-$ , $\gamma$ (R11, F7)	7 y (F11, P46)	0.9(R11)spect		Eu(n, $\gamma$ )(S20, R11, F7, F11) Sm(d, 2n)(?)(K20) Eu(d, p)(F11) Sm(d, n)(K20)
Eu 155	A	$\beta^-$ , $\gamma$	2 y (P47)	0.23(P47)	0.0844(P47)	Fiss(P47)
Eu 156	A	$\beta^-$ , $\gamma$	15.4 d (P47)	0.5, 2.5(P47)abs Al	2.0(P47)abs Pb	Fiss(P47)
Eu 157	B	$\beta^-$ , $\gamma$	15.4 h (P47)	1.7, 1.0(P47)abs Al	0.6, 0.2(P47)abs Pb	Fiss(P47)
64 Gd 158	C	$\beta^-$	60 m (P47)	2.6(P47)abs Al		Fiss(P47)
Gd 159	E	$\beta^-$	8 h (Al, H17)			Gd(n, $\gamma$ )(Al, H20, H17)
Gd	F	$\beta^-$ , $\gamma$ (F11)	155-170 d (F 11)			Eu(d, n)(F11)
65 Tb 160	A	$\beta^-$	3.9 h (H16, M13)			Tb(n, $\gamma$ )(H17, M13, H20)
Tb 160	A	$\beta^-$ , $\gamma$ (B33)	72 d (B33)	0.70(B33)abs Al		Tb(n, $\gamma$ )(B33)
66 Dy 163	C	I.T.e	1.2 m (P46)	(e $^-$ )0.13(P46)		
Dy 165	A	$\beta^-$ , $\gamma$	2.5 h (H17, P9, M13)	1.20(C31)abs; coincid; 1.18 (D33)spect 1.40 (E11)cl ch		Dy(n, $\gamma$ )(H17, H20, P9, M13, M31)



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
66 Dy (?)	F	$\beta^+$	2.2 m (P9)			Dy(n,?)(P9)
67 Ho <sup>164</sup>	F	$\beta^-$	47 m (P9)			Ho(n,2n)(?)(P9)
Ho 166	A	$\beta^-$	27.5 h (P46)	1.6(H20)abs 1.9(M31)abs		Ho(n, $\gamma$ )(H17, H20,P9,M31)
68 Er 165	F	$\beta^+$	1.1 m (P9)			Er(n,2n)(?)(P9)
Er 169 171	C	$\beta^-$	7 m (M13)			Er(n, $\gamma$ )(M13, M18)
Er 169 171	C	$\beta^-$	12 h (H17, P9)			Er(n, $\gamma$ )(H17, H20,P9,R24)
69 Tm 170	A	$\beta^-$	105 d (H20)	1.1 (P46)	No $\gamma$	Tm(n, $\gamma$ )(H20, N7)
70 Yb 169	E	K, $\gamma$	33 d (P46)		0.2, 0.4 (P46)	
Yb 175	B	$\beta^-$	45 d (A35)	.3 (S35)	No $\gamma$	Yb(n, $\gamma$ )(S35)
Yb 175	B	$\beta^-, \gamma$	4.2 d (A35)	1.15 (S35)	0.35 (P46)	Yb(n, $\gamma$ )(S35)
Yb 177	B	$\beta^-, \gamma$	1.9 h (A35) 2.4 h (P48)	.45 (S35)	0.2 (P46)	Yb(n, $\gamma$ )(S35)
71 Lu 176 (H80, M54)	A	K, $\beta^-$ (H80) L70)( $\gamma$ (F16)	7.3 x 10 <sup>10</sup> y L70)	0.215 (L70) abs Al spect; 0.40 (F16)	0.260 (F16)	Natural source (H80)
Lu 176	A	$\beta^-, \gamma, K$	3.67 h (F16, S35)	1.150 (F16)abs 1.25 (S35)		Lu(n, $\gamma$ )(H20, H17,M13, M18,F16)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev Particles	Gamma Rays	Produced by
71 Lu 177	B	$\beta^-$ , $\gamma$	6.6 d (F16) (S35)	0.440 (F16) abs 0.47 (P46)	0.2 (P46)	Lu (n, $\gamma$ ) (H17, H20, F6, F16)
72 Hf 181	A	$\beta^-$	55 d (H19)	0.8 (P46)	0.5 (P46)	Hf (n, $\gamma$ ) (H19)
73 Ta 180	A		14-21 m (B11, O1)			Ta ( $\gamma$ , n) (B11) Ta (n, 2n) (O1) (?)
Ta 180	A	K, $e^-$ , $\gamma$ (O1); $\beta^-$ (?)	8.2 h (O1)	<0.5 ( $e^-$ ) (?) (O1) abs		Ta (n, 2n) (O1, P2)
Ta 181	A	I.T., $\gamma$ , $e^-$	2.2 x 10 <sup>-5</sup> s (D53)		0.18 (D53) abs Al	Hf 181 (decay) (D53)
Ta 182	A	$\beta^-$ , $\gamma$	120 d (O1, P46)	1.0 (H37) abs; 0.98, 0.32, 0.050 (Z2)	1.6 (Z2)	Ta (n, $\gamma$ ) (O1, F6, H37) Ta (d, p) (O1, Z2)
Ta 182	A	$\beta^-$ , $\gamma$	16.2 m (P46)	0.2 (P46)		
74 W 181	E		21 m (P46)			
W 181	E		3.9 h (P46)			
W 185	B	$\beta^-$ , $\gamma$ (M36)	77 d (M36)	0.55-0.65 (F12) abs Al; 0.64- 0.72 (F12) cl ch		W (n, $\gamma$ ) (M36, F12) W (n, 2n) (M36, F12) W (d, p) (F12) Re (d, $\alpha$ ) (F12)
W 187	B	$\beta^-$ , $\gamma$ (M36)	24.2 h (F12)	1.4 (F12) abs Al cl ch (C31) abs coincide, .5 (S83)	0.87 (F12) abs Pb 0.90 (C31) coincide abs, coincide; 0.94 (M30) spect; 0.135, 0.101, 0.101, 0.086 (V6) spect conv	W (n, $\gamma$ ) (M14, Al, M36, F12) W (d, p) (F12)



Isotope Z El A	Class	Type of Radiation	Energy of Radiation in mev			Produced by
			Half-life	Particles	Gamma Rays	
75 Re	E	$\beta$ (C42)	30-55 m (C32 D9)			W(n,n)(D9,C32)
Re	E		13 m (C42)			W(p,n)(D9,C42)
Re 184	B	K, $\gamma$ , $\beta^-$	52 d (F12)	0.22-0.26 (P46)	0.85 (F12)	W(p,n)(D9,C42,F12, C32) W(d,n)(F12) Re(n,2n)(F12)
Re 186	A	$\beta^-$	92.8 h (G44)	1.07 (G44)abs Al	No $\gamma$ (C42)	Re(n, $\gamma$ )(S16,K7, Y4,F12) Re(n,2n)(S16,Y4, F12) W(p,n)(D9,C32) Re(d,p)(F12,G44) W(d,2n)(F12)
Re 187		I.T. $e^-$ , $\gamma$			.7,.48,.57,.69,.79, .86(S83).85,.10, .12(V23)	W - $\beta$ decay (S83)
Re 188	A	$\beta^-$ , $\gamma$	18.9 h (G44)	2.5 (S16)cl ch (Ku) 2.05 (G44)abs Al	0.8 (M34)spect	Re(n, $\gamma$ )(P2,K7,S16 Y4,F12) Re(d,p)(F12,G44)
76 Os 185	A	$\gamma$ , K	94.7 d (G44)			Re(d,2n)(G44)
Os 191	B	$\beta^-$ , $\gamma$ (S36)	32 h (S36) 31.9 h (G44)	1.5 (S36)abs Al 0.95 (G44)abs Al	1.17 (G44)abs Pb	Os(n, $\gamma$ )(X7,S36,Z3 G44) Os(n,2n)(?)(S36)
Os 193	B	$\beta^-$ , $\gamma$ (S36)	17 d (S36)	0.35 (S36)abs Al		Os(n, $\gamma$ )(S36,Z3)

Isotope Z El A	Class	Type of Radia- tion	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
77 Ir 190	B	$\beta^+$ , $\gamma$ , I.C.	10.7 d (G44)	.091 (G44) abs, 0.96 (P46)	.25 (G44) abs	Ir (n, 2n) (G44)
Ir 192	A	$\beta^-$ , I.T.	1.5 m (M15)		0.6 (P46)	Ir (n, $\gamma$ ) (M15)
Ir 192	A	$\beta^-$ , $\gamma$	75 d (G44)	.59 (G44) abs	.53 (G44) abs	
Ir 194	A	$\beta^-$ , $\gamma$ (M34, W29)	19 h (M15, A1) (G44)	2.2 (A2) spect, 2.18 (W29) spect; 2.11 (W29) abs A1, 3.07 (G44)	1.35 (M34) spect 0.38, 1.65 (G44) abs A1	Ir (n, $\gamma$ ) (M15) A1, P2, J4 Au (d, $\alpha$ , p) (?) Cl8 Ir (n, 2n) (G44)
78 Pt 191	D	K, $e^-$ , $\gamma$	2.9 d (P46)	0.47 (P46)	0.2 (P46)	
Pt 193	D	K, $e^-$	4.2 d (P46)	0.095 (P46)		
Pt 196	D	I.T., $e^-$ (?) (S37)	80 m (S37)			Hg (n, $\alpha$ ) (S37) Pt (d, p) (S37)
Pt 197	B	$\beta^-$	18 h (M15)	0.65 (S37) abs; 0.72 (K27) abs		Pt (n, $\gamma$ ) (M15, S37) Pt (d, p) (Cl9, S37, K27) Pt (n, 2n) (S37) Hg (n, $\alpha$ ) (S37)
Pt 197	B	$\beta^-$ , $\gamma$ (K27)	3.3 d (M15)			Pt (n, $\gamma$ ) (M15, P2) Pt (d, p) (K27)
Pt 199	A	$\beta^-$	31 m (M15)	11.8 (S37, K27) abs		Pt (n, $\gamma$ ) (M15, A1, M14, S37) Pt (d, p) (Cl9, K27, S37) Hg (n, $\alpha$ ) (S37)



Isotope Z El A	Class	Type of Radiation	Energy of Radiation in mev		Produced by
			Half-life	Particles	
79 Au 196	B	$\beta^-$	13 h (M15)		Au (n,2n) (M15)
Au 196	B	$\beta^-$ , $\gamma$ , $e^-$ (K27)	4-5 d (M15); 5.6 d (L28, K27)	0.36 (C43)	Au (n,2n) (M15) Pt (d,n) (K27)
Au 197	A	$\gamma$	7.5 d (W55)		Au 197 = X-rays (W54, W55, W56)
Au 198	A	$\beta^-$ , $\gamma$ , $e^-$	2.7 d (M15, A1)	0.8 (M15, R2) abs and cl ch; 0.78 (C31) abs coincid	Au (n, $\gamma$ ) (M15, A1, P2, D33) Au (d,p) (C18, K28) Hg (n,p) (S37)
Au 199	A	$\beta^-$ , $\gamma$ (K27)	3.3 d (M15)	1.01 (K27) abs	Pt 199 $\beta^-$ decay (M15, K27) Hg (n,p) (S37) Pt (d,n) (K27)
Au 200	D	$\beta^-$	48 m (S37, M32)	2.5 (S37) abs	Hg (n,p) (S37, M32) Tl (n, $\alpha$ ) (M32)
80 Hg 197	A	K, $\gamma$ , $e^-$ (F13)	23 h (F13)	$\sim 0.20$ (F13) abs of $e^-$ ; 0.161, 0.130 (H38) spect conv; 0.125, 0.157 (V8)	Au (d,2n) (F13, W26, K28) Hg (n,2n) (F13, W26) Hg (n, $\gamma$ ) (F13, W25, M15, A9) Pt ( $\alpha$ , n) (S37) Hg (d,p) (K29)
80 Hg 197	A	K, $\gamma$ , $e^-$ (F13)	64 h (F13)	$\sim 0.09$ (F13) abs of $e^-$ ; 0.075 (H38) spect conv	Au (d,2n) (F13, W26) Hg (n,2n) (F13, W26) Hg (n, $\gamma$ ) (F13, W26)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
80 Hg 199 201 204	D	I.T., $e^- \gamma$ (Fl3)	43 m (H10, M15)		$\sim 0.53$ (Fl3) abs of $e^-$	Hg(n,2n)(M15, H10, P2) Hg(n,2n)(?)(Fl3, W26) Hg(d,p)(K29) Pt( $\alpha$ ,n)(?)(S37) Hg( $\gamma$ , $\gamma$ )(W94)
Hg 203	C	$\beta^-$ , $\gamma$ (Fl3)	51.5 d (Fl3)	0.46 (Fl3) abs Al	0.30 (Fl3) abs Pb	Hg(n, $\gamma$ )(Fl3, W26 S37) Hg(d,p)(K29) Tl(n,p)(M32)
Hg 205	A	$\beta^-$	5.5 m (K29, M32)	1.62 (K29) abs Al		Hg(d,p)(K29) Hg(n, $\gamma$ )(Fl3, W26) Tl(n,p)(M32) Pb(n, $\alpha$ )(M32)
81 Tl 197	D	K(?), $e^-$ , $\gamma$ (K29)	10.5 h (K29)		1.0 (K29) abs Pb	Hg(d,2n)(K29)
Tl 198	D	K(?), $e^-$ (K29)	44 h (K29)			Hg(d,2n)(K29)
Tl 200	F		4 m (K3)			Au( $\alpha$ ,n)(?)(K3)
Tl 200	F		3.8 h (K3)			Au( $\alpha$ ,n)(?)(K3)
Tl 202	B	K(?), $\gamma$ , $e^-$ (K29, M32)	11.8 d (Fl14); 13 d (M32)		0.40 (M32)	Hg(d,2n)(K29) Tl(n,2n)(Fl14, M32)
Tl 204	A	$\beta^-$	4.23 m (Fl7)	1.6 (Fl7) abs; 1.77 (K29) abs Al	No $\gamma$ (Fl7)	Tl(n, $\gamma$ )(P10, P2, H10) Tl(d,p)(Fl7, K29) Tl(n,2n)(Fl7, P2 H10) Pb( $\tau$ , p, n)(B74)



Isotope			Type of Radiation		Energy of Radiation in mev		Produced by	
Z	El A	Class	ation	Half-life	Particles	Gamma Rays		
81	Tl 206	B	$\beta^-$	3.5 y (F14)	0.87 (F14) cl ch	No $\gamma$ (F14)	Tl (n, $\gamma$ ) (F17, F14) Tl (d, p) (F17, F14)	
	Tl 207 (AcC")	A	$\beta^-, \gamma$ (C60)	4.76 m (C60, S70)	1.47 (S71) abs Al		AcC 211 a decay Pb (n, p) (B16)	
	Tl 208 (ThC")	A	$\beta^-, \gamma$ (C60)	3.1 m (C60)	1.82 (S72) abs paper	2.62 (R40)	ThC 212 a decay	
	Tl 210 (RaC")	A	$\beta^-$	1.32 m (C60)	1.80 (L71) cl ch		RaC 214 a decay	
82	Pb 203	B	$\beta^+$	10.25 m (K29)	1.66 (K29) abs Al		Tl (d, 2n) (K29)	
	Pb 203	B	I. T. (?) or K (?), $e^-$ $\gamma$ (F14, K29, L33, M32)	52 h (F17, F14)		$\sim 0.45$ (F17, F14, K29) abs of $e^-$ , (F14, M32, L33) abs. Pb, (L33) spect, (M32) spect conv, 0.27 (L33, M32) spect conv abs Pb	Tl (d, 2n) (F14, K29, F17) Pb (n, 2n) (M32) Pb ( $\gamma$ , n) (B74)	
	Pb 204	B	I. T. (?), $\gamma$ , $e^-$ (F14, M32)	68 m (M32); 65 m (F14)		1.1 (F14) abs of $e^-$ , abs Pb; 0.90 (M32)	Pb (n, $\gamma$ ) or Pb (n, n) (D10, M32) Tl (d, n) (F14) Pb ( $\gamma$ , n) (B74)	
	Pb 209	A	$\beta^-$	3.0 h (T5)	0.70 (K29, F14) abs abs 0.750 (M32)		Pb (d, p) (T5, K29, F14, F15) Pb (n, $\gamma$ ) (M32) Bi (n, p) (M32)	

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
82 Pb 210 (RaD)	A	$\beta^-$ , $\gamma$ (R40)	22 y (C60)	0.0255(L72)spect	0.047(R40)	RaC"210 $\beta^-$ decay RaC"214 $\alpha$ decay
Pb 211 (AcB)	A	$\beta^-$ , $\gamma$ (S71)	36.1 m (S70)	0.5, 1.40(S71)abs Al	0.8(S71)abs	AcA 215 $\alpha$ decay
Pb 212 (ThB)	A	$\beta^-$ , $\gamma$ (R40)	10.6 h (C60)	0.36(S72)spect		ThA 216 $\alpha$ decay
Pb 214 (RaB)	A	$\beta^-$ , $\gamma$ (R40)	26.8 m (C60)	0.65(S72)spect		RaA 218 $\alpha$ decay
Pb 215	D	I.T., $e^-$	1.6 m (W27)		$\sim 0.3$ (W27)abs of $e^-$	Pb x-rays (W27)
83 Bi 207	A	K(?), $e^-$ , $\gamma$ (L33)	6.4 d (K29)		0.74(K29)abs of $e^-$ 0.93(F14)abs of $e^-$ 1.1(F14)abs Pb	Pb(d,n)(F15, F14 K29)
Bi 205	B	K, $e^-$ , $\gamma$	10-15 h (P46)			
Bi 206	A	K, $e^-$ , $\gamma$	6.4 d (P46)		0.93(P46)	
Bi 208	B	K, $e^-$ , $\beta^-$ , $\gamma$	10 <sup>4</sup> y (P46)			
Bi 210 (RaE)	A	$\beta^-$	5.0 d (C60)	1.17(F30, N40, L76)spect	No $\gamma$	RaD 210 $\beta^-$ decay Bi(d,p)(L13, C26 H27) Bi(n, $\gamma$ )(M29)
Bi 211 (AcC)	A	$\alpha$ (99.68%) (C60), $\gamma$ (R40); $\beta^-$ (0.32%)(C60) $\gamma$ (C60)	2.16 m (C60)	6.619( $\alpha$ )(H81) spect		AcB 211 $\beta^-$ decay



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
83 Bi 212 (ThC)	A	$\alpha$ (33.7%)(K50), $\gamma$ (R40); $\beta$ (66.3%)(K50), $\gamma$ (C60)	60.5 m(C60)	6.054( $\alpha$ )(B70, H81)spect;2.20 ( $\beta$ )(S72)spect		ThB 212 $\beta$ -decay
B1 214 (RaC)	A	$\alpha$ (0.04%)(C60); $\beta$ (99.96%)( C60), $\gamma$ (R40)	19.7 m(C60)	5.502( $\alpha$ )(L73) spect; 3.15( $\beta$ ) (S72)abs A1	1.8(R40)	RaB 214 $\beta$ -decay
84 Po 206	A	K, $\alpha$ (10%) $\gamma$ (P46)	9 d(P46)	$\alpha$ 5.2(P46)		
Po 207	A	K	5.7 h(P46)			
Po 208	B	$\alpha$	3 y(P46)	$\alpha$ 5.14(P46)		
Po 210	A	$\alpha$ , $\gamma$ (R40)	140 d(C60)	5.298(H81)spect		RaE 210 $\beta$ -decay (L13,C26,H27) Bi(d,n)(V4,C26, H27)
Po 211 (AcC')	A	$\alpha$	$5 \times 10^{-3}$ s (C60)	7.434(L73)spect		AcC 211 $\beta$ -decay 85 211 K decay (C46,C23)
Po 212 (ThC')	A	$\alpha$	$3 \times 10^{-7}$ s (D50)	8.776(B70,H81) spect		ThC 212 $\beta$ -decay
Po 213	A	$\alpha$	$10^{-5}$ s (P46)	$\alpha$ 8.336		
Po214 (RaC')	A	$\alpha$	$1.5 \times 10^{-4}$ s (D50,R41, W50)	7.680(B70,H81) spect		RaC 214 $\beta$ -decay
Po 215 (AcA)	A	$\alpha$	$1.83 \times 10^{-3}$ sec(W50)	7.365(L73)spect		An 219 $\alpha$ decay

Isotope Z El A	Class	Type of Radiation	Energy of Radiation in mev			Produced by
			Half-life	Particles	Gamma Rays	
84 Po 216 (Tha)	A	$\alpha$ (~100%); $\beta$ (0.014%)(K33)	0.158 s (W50)	6.774( $\alpha$ )(B70,H81) spect		Tn 220 $\alpha$ decay
Po 217	A	$\alpha$	<1 h(P46)			
Po 218 (RaA)	A	$\alpha$ (99.96%); $\beta$ (0.04%)(K51)	3.05 m(C60)	5.998( $\alpha$ )(B70,H81) spect		Rn 222 $\alpha$ decay
85 At 211	A	$\alpha$ (60%)(C46); K (40%)(C46)	7.5 h(C46, C23)	5.94( $\alpha$ )(C46)abs		Bi( $\alpha$ ,2n)(C46,C23)
At 215	F	$\alpha$	Short	8.4		
At 216	F	$\alpha$ (K33)	Short(<54 sec)(K33)	7.64(K33)ion ch		ThA 216 $\beta$ -decay (K33)
At 218	F	$\alpha$ (K51)	Several sec (?)(K51)	6.63(K51)ion ch		RaA 218 $\beta$ -decay (K51)
86 Rn 219 (An)	A	$\alpha$	3.92 s(C60)	6.824(H81,L73) spect		AcX 223 $\alpha$ decay
Rn 220 (Tn)	A	$\alpha$	54.5 s(C60)	6.282(B70,H81) spect		ThX 224 $\alpha$ decay
Rn 221	A	$\alpha$	< 1 h(P46)			
Rn 222	A	$\alpha$	3.825 d(C60)	5.486(B70,H81) spect		Ra 226 $\alpha$ decay
87 Fa 223 (AcK)	E	$\beta^-$ , $\gamma$ (P41, P43)	21 m(P40, P43)	1.20(P42,P41)cl ch	>3(P41)cl ch	Ac 227 $\alpha$ decay (P40)
88 Ra 222	A	$\alpha$	0.5m(P46)			



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
88 Ra 223 (AcX)	A	$\alpha, \gamma$ (R40)	11.2 d(C60)	6.717(L73)spect		RdAc 227 $\alpha$ decay
Ra 224 (ThX)	A	$\alpha$	3.64 d(L71)	5.681(B70)spect		RdTh 228 $\alpha$ decay
Ra 226	A	$\alpha, \gamma$ (C60)	1590 y(C60)	4.791(L73)spect	0.19(R40)	Io 230 $\alpha$ decay
Ra 228 (MsThI)	A	$\beta^-$	6.7 y(C60)	0.053(L72)spect abs Al		Th 232 $\alpha$ decay
89 Ac 227	A	$\alpha$ (1%)(P40); $\beta^-$ (99%)(P40)	13.5 y(C60) 21 y(J5)	5.0(a)(P40)abs air; 0.220( $\beta^-$ ) (H82)spect	No $\gamma$ (P43)	Pa 231 $\alpha$ decay
Ac 228 (MsTh2)	A	$\beta^-, \gamma$ (C60); $\alpha$ (G40)	6.13 h(C60)	1.55( $\beta^-$ )(L6) spect; 4.5( $\alpha$ ) (G40)abs air		MsThI 228 $\beta^-$ decay
90 Th 226	A		30 m(P46)			
Th 227 (RdAc)	A	$\alpha, \gamma$ (C60)	18.9 d(C60)	6.049(L73)spect		Ac 227 $\beta^-$ decay
Th 228 (RdTh)	A	$\alpha, \gamma$ (C60)	1.90 y(C60)	5.418(L73)spect		MsTh2 228 $\beta^-$ decay
Th 230 (Io)	A	$\alpha, \gamma$ (W53)	8.3 x 10 <sup>4</sup> y (C60)	4.66(G41)abs air 4.81(W51)calor		UI 234 $\alpha$ decay
Th 231 (UY)	A	$\beta^-$	24.6 h(C60) 24.0 h(G43)	$\sim 0.2$ (E30)abs		AcU 235 $\alpha$ decay
Th 232	A	$\alpha$	1.39 x 10 <sup>10</sup> y(K50)	4.20(S73)ion ch		Th(n,2n)(N5) Natural source (C62, S76)

Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
90 Th 233	A	$\beta^-$	23 m (G12)			Th ( $n, \gamma$ ) (M17)
Th 234 (UX <sub>1</sub> )	A	$\beta^-$ , $\gamma$ (M60, F40)	24.5 d (C60); 24.1 d (S70)	0.130, 0.300 (M61) cl ch; 0.11, 0.20 (F40) abs Al; 0.13 (S72) abs Al spect	0.092 (M60) (1%) (F40)	U <sub>1</sub> 238 $\alpha$ decay
91 Pa 231	A	$\alpha$ , $\gamma$ (C60)	$3.2 \times 10^4$ y (G42)	5.049 (R42) spect		UY 231 $\beta^-$ decay
Pa 233	A	$\beta^-$ , $\gamma$ , $e^-$ (H40)	27.4 d (G12)	0.4 (S38) abs Al 0.23 (H40) spect	e lines at 0.063 0.077, 0.192, 0.293 (H40) spect	Th 233 $\beta^-$ decay (S38, (G12, H39)
Pa 234 (UZ)	A	$\beta^-$ , $\gamma$ (F40)	6.7 h (C60)	0.56, 1.55 (F40) abs Al	0.70 (F40) abs Pb, W	Ux <sub>2</sub> 234 I.T. (F40)
Pa 234 (UX <sub>2</sub> )	A	$\beta^-$ , $\gamma$ (M61); I.T. (0.15%) (?) (F40)	1.14 m (C60)	2.32 (S72) abs Al 1.52 (5%), 2.32 (95%) (M61) spect	0.802 (5%) (M61) spect conv; 0.782, 0.822 (B32) spect conv	UX <sub>1</sub> 234 $\beta^-$ decay
92 U 234	A	$\alpha$	$2.33 \times 10^5$ y (N41) (P46)	4.71 (R43) cl ch; 4.78 (S75) abs air; 4.76 (S77) ion ch		Pa 234 $\beta^-$ decay
U 235 (AcU')	A	$\alpha$	$7.07 \times 10^8$ y (N41)	4.52 (W52) cl ch		Natural source (D51)
U 237	A	$\beta^-$ , $\gamma$ (M37)	$\sim 7$ d (M37, N8)	0.26 (M37) abs	0.5 (P46)	U ( $n, 2n$ ) (M37, N8)



Isotope Z El A	Class	Type of Radiation	Half-life	Energy of Radiation in mev		Produced by
				Particles	Gamma Rays	
92 U 238 (U <sub>1</sub> )	A	$\alpha$	$4.5 \times 10^9$ y (N41)	4.15(R43)el oh; 4.23(S75)abs air; 4.21(S77) ion oh		Natural source(B72)
U 239	A	$\beta^-$	23 m(11,S4)	0.56, 1.2	0.076	U( $\alpha$ , $\gamma$ )(H18,H14,11, M19,S44)
93 Np 234	B	K, $\gamma$	4.4d(P46)			
Np 235	B	K, $\gamma$	>1 y			
Np 236	A	$\beta^-$				
Np 237	A	$\alpha$	$2.25 \times 10^6$ y (P46)	$\alpha$ 4.77		
Np 238	A	$\beta^-$	2.0 d(P46)			
Np 239	A	$\beta^-$ , $\gamma$	2.3 d(M28, M19)	0.47(M28)abs	0.22, 0.27(H25) spect conv spect	U 239 $\beta$ -decay(M28 S39,S44)
94 Pu 238	A	$\alpha$	50 y(P46)	$\alpha$ 5.4(P46)		
Pu 239	A	$\alpha$	$2.41 \times 10^4$ y	$\alpha$ 5.144(P46)		
Pu 241	A	$\beta^-$				
95 Am 241	A	$\alpha$	500 y(P46)			
Am 242	A	$\beta^-$	18 h(P46)			
96 Cm 240	A	$\alpha$	30 d(P46)			
Cm 242	A	$\alpha$	150 d(P46)			

## REFERENCES

- (A1) Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti, and Segre',  
Proc. Roy. Soc. London A149, 522 (1935).
- (A2) Alichanian, Alichanow, and Dzelepov, Physik. Zeits.  
Sowjetunion 10, 78 (1936).
- (A3) Andersen, Zeits. f. physik. Chemie B32, 237 (1936).
- (A4) Alvarez, Phys. Rev. 54, 486 (1938).
- (A5) Aten, Jr., Bakker, and Heyn, Nature 143, 679 (1939).
- (A6) Abelson, Phys. Rev. 56, 1 (1939).
- (A7) Alvarez and Cornog, Phys. Rev. 56, 613 (1939), and private  
communication.
- (A8) Alexeeva, Comptes rendus U.R.S.S. 18, 553 (1938).
- (A9) Anderson, Nature 137, 457 (1936).
- (A10) Amaki and Sugimoto, Sci. Papers Inst. Phys. Chem. Research  
(Tokyo) No. 853, p. 1650 (1938).
- (A11) Alvarez, private communication.
- (A12) Alvarez, Helmholtz, and Nelson, Phys. Rev. 57, 660 (1940).
- (A13) Allen and Hurst, Proc. Phys. Soc. London 52, 501 (1940).
- (A14) Amaki, Iimori, and Sugimoto, Phys. Rev. 57, 751 (1940).
- (A15) Akabori et al., Proc. Phys. Math. Soc. Japan 23, 599 (1941).
- (A16) Alvarez and Cornog, Phys. Rev. 58, 197 (1940).
- (A17) Allen, Pool, Kurbatov, and Quill, Phys. Rev. 60, 425 (1941).
- (A18) Allen, Phys. Rev. 61, 692 (1942).
- (A30) Alvarez and Cornog, Phys. Rev. 56, 379 (1939).
- (A31) Aston, Mass Spectra and Isotopes (E. Arnold and Company,  
London, 1942).
- (A32) Aston, Nature 137, 613 (1936).
- (A33) Aston, Proc. Roy. Soc. London A146, 46 (1934).



- (A34) Allen, Mitchell, Turney, Ramsey, Phys. R. 71, 324 (1947).
- (A35) Atterling, Bahr, Sigurgeirsson, Arkiv. Mat., Ast.,  
Fysk A32, No. 2 (1945).
- (B1) Bjerge and Broström, Kgl. Danske Vid. Sels. Math.-Fys.  
Medd. 16, No. 8 (1938).
- (B2) Bjerge and Brostrom, Nature 138, 400 (1936).
- (B3) Bjerge, Nature 138, 400 (1936).
- (B4) Bayley and Crane, Phys. Rev. 52, 604 (1937).
- (B5) Bethe, Hoyle, and Peierls, Nature 143, 200 (1939).
- (B6) Bjerge, Nature 139, 757 (1937).
- (B7) Borst, Phys. Rev. 61, 106 (1942).
- (B8) Barkas, Creutz, Delsasso, Sutton, and White, Phys. Rev. 58,  
383 (1940).
- (B9) Burcham, Goldhaber, and Hill, Nature 141, 510 (1938).
- (B10) Brown and Mitchell, Phys. Rev. 50, 593 (1936).
- (B11) Bothe and Gentner, Naturwiss. 25, 191 (1937).
- (B12) Barnes and Valley, Phys. Rev. 53, 946 (1938).
- (B13) Buck, Phys. Rev. 54, 1025 (1938).
- (B14) Bacon, Grisewood, and van der Merwe, Phys. Rev. 59, 531  
(1941).
- (B15) Bretscher and Cook, Nature 143, 560 (1939).
- (B16) Bretscher and Cook, Nature 146, 430 (1940).
- (B17) Barnes, Phys. Rev. 56, 414 (1939).
- (B18) Barnes and Aradine, Phys. Rev. 55, 50 (1939).
- (B19) Bacon, Grisewood, and van der Merwe, Phys. Rev. 54, 315  
(1938).

- (B20) Bothe and Gentner, Zeits.f.Physik 112, 45 (1939).
- (B21) Brandt, Zeits.f.Physik 108, 726 (1938).
- (B22) Becker and Gaerttner, Phys. Rev. 56, 854 (1939).
- (B23) Barkas, Phys. Rev. 56, 287 (1939).
- (B24) Barresi and Cacciapuoti, Ricerca Scient. 10, 464 (1939).
- (B25) Bethe and Henderson, Phys. Rev. 56, 1060 (1939).
- (B26) Bacon, Grisewood, and van der Merwe, Phys. Rev. 56, 1168 (1939).
- (B27) Barkas, Creutz, Delsasso, Fox, and White, Phys. Rev. 57, 562 (1940).
- (B28) Bothe and Flammersfeld, Naturwiss. 29, 194 (1941).
- (B29) Born and Seelmann-Eggebert, Naturwiss. 31, 86 (1943).
- (B30) Born and Seelmann-Eggebert, Naturwiss. 31, 201 (1943).
- (B31) Born and Seelmann-Eggebert, Naturwiss. 31, 420 (1943).
- (B32) Bradt, Heine, and Scherrer, Helv. Phys. Acta 16, 455 (1943).
- (B33) Bothe, Naturwiss. 31, 551 (1943).
- (B41) Barkas, Creutz, Delsasso, and Sutton, Phys. Rev. 57, 1087 (1940).
- (B48) Barkas, Creutz, Delsasso, Sutton, and White, Phys. Rev. 58, 194 (1940).
- (B49) Barkas, Creutz, Delsasso, Sutton, and White, Phys. Rev. 58, 383 (1940).
- (B50) Bower and Burchem, Proc. Roy. Soc. London A173, 379 (1940).
- (B60) Blewett, Phys. Rev. 49, 900 (1936).
- (B70) Briggs, Proc. Roy. Soc. London A157, 183 (1936).



- (B71) Bramley and Brewer, Phys. Rev. 53, 502 (1938).
- (B72) Becquerel, Comptes rendus 122, 420, 501, 559, 609, 762, 1086 (1896).
- (B73) Bradt, Gugelot, Kuber, Medicus, Preiswerk, Scherrer, Phys. Rev. 68, 57 (1945).
- (B74) Baldwin, and Klaiber, Phys. Rev. 70, 259 (1946).
- (C1) Crane, Delsasso, Fowler, and Lauritsen, Phys. Rev. 47, 971 (1935).
- (C2) Crane, Delsasso, Fowler, and Lauritsen, Phys. Rev. 47, 887 (1935).
- (C3) Crane and Lauritsen, Phys. Rev. 45, 497 (1934).
- (C4) Cockcroft, Gilbert, and Walton, Proc. Roy. Soc. London A148, 225 (1935).
- (C5) Chang, Goldhaber, and Sagane, Nature 139, 962 (1937).
- (C6) Cork, Richardson, and Kurie, Phys. Rev. 49, 208 (1936).
- (C7) Curie and Joliot, Comptes rendus 198, 254 (1934).
- (C8) Cacciapuoti, Nuovo Cimento 15, 213 (1938).
- (C9) Chichoki and Soltan, Comptes rendus 207, 423 (1938).
- (C10) Collins, Waldman, and Stubblefield, Phys. Rev. 55, 507 (1939).
- (C11) Curtis and Cork, Phys. Rev. 53, 681 (1938).
- (C12) Cacciapuoti, Phys. Rev. 55, 110 (1939).
- (C13) Crittenden, Jr., Phys. Rev. 56, 709 (1939).
- (C14) Cork and Lawson, Phys. Rev. 56, 291 (1939).
- (C15) Cornog and Libby, Phys. Rev. 59, 1046 (1941).
- (C16) Curie and Savitch, Comptes rendus 208, 343 (1939).

- (C17) Cook and McDaniels, Phys. Rev. 62, 412 (1942).
- (C18) Cork and Thornton, Phys. Rev. 51, 59 (1937).
- (C19) Cork and Lawrence, Phys. Rev. 49, 788 (1936).
- (C20) Curtis, Phys. Rev. 55, 1136 (1939).
- (C21) Cork, Hadley, and Kent, Phys. Rev. 61, 388 (1942).
- (C22) Clancy, Phys. Rev. 60, 87 (1941); 59, 686 (1941).
- (C23) Corson, Mackenzie, and Segre, Phys. Rev. 57, 459, 1087 (1940).
- (C24) Cacciapuoti and Segre, Phys. Rev. 52, 1252 (1937).
- (C25) Cooley, Yost, and McMillan, J. Am. Chem. Soc. 61, 2970 (1939).
- (C26) Cork, Halpern, and Tatel, Phys. Rev. 57, 371 (1940).
- (C27) Creutz, Fox, and Sutton, Phys. Rev. 57, 567 (1940).
- (C28) Curran, Dee, and Strothers, Proc. Roy. Soc. London A174, 546 (1940).
- (C29) Curran and Strothers, Proc. Roy. Soc. London A172, 72 (1939).
- (C30) Cork and Smith, Phys. Rev. 60, 480 (1941).
- (C31) Clark, Phys. Rev. 61, 242 (1942); 61, 203 (1942).
- (C32) Creutz, Barkas, and Furman, Phys. Rev. 58, 1008 (1940).
- (C41) Creutz, Delsasso, Sutton, White, and Barkas, Phys. Rev. 58, 481 (1940).
- (C42) Creutz, private communication.
- (C43) Cork and Halpern, Phys. Rev. 57, 1121 (1940).
- (C44) Curtis and Richardson, Phys. Rev. 57, 1121 (1940).
- (C45) Clancy, Phys. Rev. 58, 88 (1940).
- (C46) Corson, Mackenzie, and Segre, Phys. Rev. 58, 672 (1940).
- (C47) Curran and Strothers, Proc. Camb. Phil. Soc. 36, 252 (1940).



- (C50) Cohen, Phys. Rev. 63, 219 (1943).
- (C51) Cook, Phys. Rev. 64, 278 (1943).
- (C60) Curie, Debierne, Eve, Geiger, Hahn, Lind, St. Meyer,  
Rutherford, and Schweidler, Rev. Mod. Phys. 3, 427 (1931).  
Summarizes the results of various investigators.
- (C61) Campbell and Wood, Proc. Camb. Phil. Soc. 14, 15 (1906).  
Campbell, Proc. Camb. Phil. Soc. 14, 211 (1907), 557 (1908).
- (C62) Curie, Mme., Comptes rendus 126, 1101 (1898).
- (D1) Delsasso, Fowler, and Lauritsen, Phys. Rev. 48, 848 (1935).
- (D2) Dubridge, Barnes, Buck, and Strain, Phys. Rev. 53, 447 (1938).
- (D3) Dubridge, Barnes, Wiig, Buck, and Strain, Phys. Rev. 53,  
326 (1938).
- (D4) Delsasso, Ridenour, Sherr, and White, Phys. Rev. 55, 113 (1939)
- (D5) Darling, Curtis, and Cork, Phys. Rev. 51, 1010 (1937).
- (D6) Dodson and Fowler, Phys. Rev. 55, 880 (1939).
- (D7) DeVries and Veldkamp, Physica 5, 249 (1938).
- (D8) Dode and Pontecorvo, Comptes rendus 207, 287 (1938).
- (D9) Dubridge, private communication; includes work of entire  
Rochester group.
- (D10) DeVries and Diemer, Physica 6, 599 (1939).
- (D11) Dubridge and Marshall, Phys. Rev. 56, 706 (1939).
- (D13) Dubridge and Marshall, Phys. Rev. 57, 348 (1940).
- (D14) Dickson, McDaniel, and Konopinski, Phys. Rev. 57, 351  
(1940).
- (D15) Deutsch and Roberts, Phys. Rev. 60, 362 (1941).

- (D16) Deutsch, Downing, Elliott, Irvine, and Roberts, Phys. Rev. 62, 3 (1942).
- (D17) Deutsch and Elliott, Phys. Rev. 62, 558 (1942).
- (D18) Doran and Henderson, Phys. Rev. 60, 411 (1941).
- (D19) Deutsch, Roberts, and Elliott, Phys. Rev. 61, 389 (1942).
- (D20) DeVault and Libby, Phys. Rev. 58, 688 (1940).
- (D21) Deutsch, Phys. Rev. 61, 672 (1942).
- (D22) Davidson, Jr., Phys. Rev. 57, 1086 (1940).
- (D23) Downing and Roberts, Phys. Rev. 59, 940 (1941).
- (D24) Davidson, Jr., private communication.
- (D25) Dubridge and Marshall, Phys. Rev. 58, 7 (1940).
- (D26) Delsasso, White, Barkas, and Creutz, Phys. Rev. 58, 586 (1940).
- (D27) Dodson and Fowler, Phys. Rev. 57, 966 (1940).
- (D28) Downing, Deutsch, and Roberts, Phys. Rev. 60, 470 (1941).
- (D29) Deutsch, Phys. Rev. 59, 940 (1941).
- (D30) Downing, Deutsch, and Roberts, Phys. Rev. 61, 389 (1942).
- (D31) Downing, Deutsch, and Roberts, Phys. Rev. 61, 686 (1942).
- (D32) DeWire, Pool, and Kurbatov, Phys. Rev. 61, 564 (1942); 61, 544 (1942).
- (D33) Dzelepov and Konstantinov, Comptes rendus U.R.S.S. 30, 701 (1941).
- (D34) Deutsch, private communication to Mandeville and Fulbright; Phys. Rev. 64, 265 (1943).
- (D35) Deutsch and Elliott, Phys. Rev. 65, 211 (1944).



- (D40) Dempster, Phys. Rev. 55, 794 (1939).
- (D41) Dempster, Phys. Rev. 49, 947 (1936).
- (D42) Dempster, Phys. Rev. 53, 727 (1938).
- (D43) Dempster, Phys. Rev. 52, 1074 (1937).
- (D44) Dempster, Nature 136, 65 (1935).
- (D45) Dempster, Nature 138, 120 (1936).
- (D50) Dunworth, Nature 144, 152 (1939).
- (D51) Dempster, Nature 136, 180 (1935).
- (D52) Deutsch, Elliot, and Roberts, Phys. Rev. 68, 193 (1945).
- (D53) DeBenedetti, and McGowan, Phys. Rev. 70, 567 (1946).
  
- (E1) Ellis and Henderson, Nature 135, 429 (1935).
- (E2) Ellis and Henderson, Proc. Roy. Soc. London A156, 358 (1936).
- (E3) Ewing, Perry, and McCreary, Phys. Rev. 55, 1136 (1936).
- (E4) Elliott and King, Phys. Rev. 59, 403 (1941).
- (E5) Ewing, private communication from Barnes.
- (E6) Enns, Phys. Rev. 56, 872 (1939).
- (E7) Elliott, Deutsch, and Roberts, Phys. Rev. 61, 99 (1942).
- (E8) Elliott, Deutsch, and Roberts, Phys. Rev. 63, 386 (1943).
- (E9) Elliott and Deutsch, Phys. Rev. 63, 321 (1943).
- (E10) Elliott and Deutsch, Phys. Rev. 63, 457 (1943).
- (E11) Eklund, Arkiv.f.Mat. Astron. Fysik A28, No. 3 (1941).
- (E12) Elliott and Deutsch, Phys. Rev. 64, 321 (1943).
- (E13) Elliott and Deutsch, Phys. Rev. 63, 219 (1943).
- (E20) Ewald, private communication to Flugge and Mattauch;  
Ber. d. D. Chem. Ges. 76, 1 (1943).
- (E30) Erckova, J. Physique 8, 501 (1937).

- (F1) Fowler, Delsasso, and Lauritsen, Phys. Rev. 49, 561 (1936).
- (F2) Frisch, Nature 133, 721 (1934).
- (F3) Fahlenbach, Zeits. f. Physik 96, 503 (1935).
- (F4) Frisch, Nature 136, 220 (1935).
- (F5) Feather and Dunworth, Proc. Roy. Soc. London A168, 566 (1938).
- (F6) Fomin and Houtermans, Physik. Zeits. Sowjetunion 9, 273 (1936).
- (F7) Fajans and Stewart, Phys. Rev. 56, 625 (1939).
- (F8) Friedlander, private communication.
- (F9) Fledmeier and Collins, Phys. Rev. 59, 937 (1941).
- (F10) Fermi and Segre, Phys. Rev. 59, 680 (1941).
- (F11) Fajans and Voigt, Phys. Rev. 60, 533 (1941).
- (F12) Fajans and Sullivan, Phys. Rev. 58, 276 (1940).
- (F13) Friedlander and Wu, Phys. Rev. 63, 227 (1943).
- (F14) Fajans and Voigt, Phys. Rev. 60, 619 (1941).
- (F15) Fajans and Voigt, Phys. Rev. 60, 626 (1941).
- (F16) Flammersfeld and Mattauach, Naturwiss. 31, 66 (1943).
- (F17) Fajans and Voigt, Phys. Rev. 58, 177 (1940).
- (F30) Flammersfeld, Zeits. f. Physik 112, 727 (1939).
- (F40) Feather and Bretscher, Proc. Roy. Soc. London A165, 530 (1938).
- (F41) Friedlander, H., Seren, and Turkel, Phys. Rev. 72, 23 (1947).
- (G2) Gentner and Segre, Phys. Rev. 55, 814 (1939).
- (G3) Guthrie, Phys. Rev. 60, 746 (1941).
- (G4) Gaerttner, Turin, and Crane, Phys. Rev. 49, 793 (1936).



- (G5) Goldhaber, Hill, and Szilard, Phys. Rev. 55, 47 (1939);  
Nature 142, 521 (1938).
- (G6) Grahame and Seaborg, Phys. Rev. 54, 240 (1938).
- (G7) v.Grosse, Booth, and Dunning, Phys. Rev. 56, 382 (1939).
- (G8) Grahame and Walke, Phys. Rev. 60, 909 (1941).
- (G9) Glasoe and Steigman, Phys. Rev. 57, 566 (1940).
- (G10) Gamertsfelder, Phys. Rev. 63, 60 (1943).
- (G11) Gotte, Naturwiss. 28, 449 (1940).
- (G12) v.Grosse, Booth, and Dunning, Phys. Rev. 59, 322 (1941).
- (G13) Gotte, Naturwiss, 29, 496 (1941).
- (G14) Gotte, Naturwiss. 30, 108 (1942).
- (G15) Gadsinski, Golotzwan, and Danilenko, J. Exper. Theor.  
Physik 10, 1 (1940).
- (G16) Goldhaber, Kaliber, and Scharff-Goldhaber, Bull. Am. Phys.  
Soc. 18, No. 6, 6 (1943); Phys. Rev. 65, 61 (1944).
- (G18) v. Grosse and Booth, Phys. Rev. 57, 664 (1940).
- (G19) Gotte, private communication to Hahn and Strassmann, Natur-  
wiss. 31, 499 (1943).
- (G21) Glasoe and Steigman, Phys. Rev. 58, 1 (1940).
- (G22) Grinberg and Roussinow, Phys. Rev. 58, 181 (1940).
- (G40) Gueben, Ann. Soc. Sci. Bruxelles B52, 60 (1932); B53, 115  
(1933).
- (G41) Geiger, Zeits. f. Physik X8, 45 (1922).
- (G42) v.Grosse, J. Am. Chem. Soc. 52, 1742 (1930).
- (G43) Gratias and Collie, Proc. Roy. Soc. A135, 299 (1932).

- (G44) Goodman and Pool, Phys. Rev. 71, 288 (1947).
- (H1) Hibdon, Pool, and Kurbatov, Bull. Am. Phys. Soc. 18, No. 2, 8 (1943); Phys. Rev. 63, 462 (1943).
- (H2) Hill and Valley, Phys. Rev. 55, 678 (1939).
- (H3) Hafstad and Tuve, Phys. Rev. 48, 306 (1935).
- (H4) Henderson, Phys. Rev. 48, 855 (1935).
- (H5) Hurst and Walke, Phys. Rev. 51, 1033 (1937).
- (H6) Hemmendinger, Phys. Rev. 55, 604 (1939).
- (H7) Heyn, Physica 4, 160 (1937).
- (H8) Heyn, Physica 4, 1224 (1937).
- (H9) Helmholtz, Phys. Rev. 60, 415 (1941).
- (H10) Heyn, Nature 139, 842 (1937).
- (H11) Heyn, Aten, Jr., and Bakker, Nature 143, 516 (1939).
- (H12) Hemmendinger, Phys. Rev. 58, 939 (1940).
- (H13) Helmholtz, Pecher, and Stout, Phys. Rev. 59, 902 (1941).
- (H14) Hahn and Strassmann, Naturwiss. 27, 11 (1939).
- (H15) Hahn and Strassmann, Naturwiss. 27, 89 (1939).
- (H16) Hevesy and Levi, Nature 136, 103 (1935).
- (H17) Hevesy and Levi, Nature 137, 185 (1936).
- (H18) Hahn, Meitner, and Strassmann, Zeits. f. Physik 106, 249 (1937).
- (H19) Hevesy and Levi, Kgl. Danske Vid. Sels. Math.-Fys. Medd. 15, No. 11 (1938).
- (H20) Hevesy and Levi, Kgl. Danske Vid. Sels. Math.-Fys. Medd. 14, No. 5 (1936).
- (H21) Henderson and Doran, Phys. Rev. 56, 123 (1939).



- (H22) Hahn and Strassmann, Naturwiss. 27, 529 (1939).
- (H23) Hahn and Strassmann, Naturwiss. 27, 451 (1939).
- (H24) Hahn, Strassmann, and Flugge, Naturwiss. 27, 544 (1939).
- (H25) Helmholtz, private communication.
- (H26) Helmholtz, Phys. Rev. 57, 248 (1940).
- (H27) Hurst, Latham, and Lewis, Proc. Roy. Soc. London A174, 126 (1940).
- (H28) Hahn and Strassmann, Naturwiss. 28, 54 (1940).
- (H29) Hahn and Strassmann, Naturwiss. 28, 61 (1940).
- (H30) Hill, Phys. Rev. 57, 567 (1940).
- (H31) Hoag, Phys. Rev. 57, 937 (1940).
- (H32) Haggstrom, Phys. Rev. 62, 144 (1942).
- (H33) Helmholtz, Phys. Rev. 62, 301 (1942).
- (H34) Helmholtz, Phys. Rev. 60, 160 (1941).
- (H35) Hales and Jordan, Phys. Rev. 62, 553 (1942).
- (H36) Hull and Seelig, Phys. Rev. 60, 553 (1941).
- (H37) Houtermans, Naturwiss. 28, 578 (1940).
- (H38) Helmholtz, Phys. Rev. 61, 204 (1942).
- (H39) Hahn and Strassmann, Naturwiss. 29, 285 (1941).
- (H40) Haggstrom, Phys. Rev. 59, 322 (1941).
- (H41) Hahn and Strassmann, Naturwiss. 29, 369 (1941).
- (H42) Hahn and Strassmann, Naturwiss. 28, 543 (1940).
- (H43) Huber, Lienhard, Scherrer, and Waffler, Helv. Phys. Acta 15 312 (1942).
- (H44) Huber, Lienhard, Scherrer, and Waffler, Helv. Phys. Acta 16, 33 (1943).
- (H45) Huber, Lienhard, and Waffler, Helv. Phys. Acta 16, 226 (1943).

- (H46) Hahn and Strassmann, Naturwiss. 28, 455 (1940).
- (H47) Hahn and Strassmann, Naturwiss. 31, 249 (1943).
- (H48) Hahn and Strassmann, Naturwiss. 30, 324 (1942).
- (H49) Hales and Jordan, Phys. Rev. 64, 202 (1943).
- (H50) Hurst and Pool. Bull. Am. Phys. Soc. 18, No. 6, 5 (1943);  
Phys. Rev. 65, 60 (1944).
- (H51) Hancock and Butler, Phys. Rev. 57, 1088 (1940).
- (H53) Hendricks, Bryner, Thomas, and Ivie, J. Phys. Chem. 47, 469  
(1943)
- (H54) Huber, Lienhard, Scherrer, and Waffler, Helv. Phys. Acta  
16, 431 (1943).
- (H55) Hahn and Strassmann, Naturwiss. 31, 499 (1943).
- (H56) Hahn and Strassmann, Zeits. f. Physik 121, 729 (1943).
- (H57) Hahn and Strassmann, Physik. Zeits. 40, 673 (1939).
- (H58) Huber, Lienhard, Scherrer, and Waffler, Phys. Rev. 60, 910  
(1941).
- (H59) Hurst and Pool, Bull. Am. Phys. Soc. 19, No. 2, 13 (1944).
- (H60) Hibdon, Pool, and Kurbatov, Bull. Am. Phys. Soc. 19, No. 2,  
13 (1944).
- (H70) Hall and Jones, J. Am. Chem. Soc. 58, 1915 (1936).
- (H71) Hoff Lu, Phys. Rev. 53, 845 (1938).
- (H80) Heyden and Wefelmeier, Naturwiss. 26, 612 (1938).
- (H81) Holloway and Livingston, Phys. Rev. 54, 18 (1938). Sum-  
marizes the results of various investigators.
- (H82) Hull, Libby, and Latimer, J. Am. Chem. Soc. 57, 1649 (1935).
- (H83) Hevesy and Paneth, Radioactivity (Oxford University Press)  
(1938).



- (H84) Hemmendinger and Smythe, Phys. Rev. 51, 1052 (1937).
- (H85) Hevesy and Pahl, Nature 130, 846 (1932).
- (H86) Hosemann, Zeits. f. Physik 99, 405 (1935). Half-life recalculated according to (W40).
- (H87) Henderson, Phys. Rev. 55, 238 (1938).
- (H88) Hevesy, Naturwiss 23, 583 (1935)
- (H89) Hahn, Strassmann, and Walling, Naturwiss. 25 189 (1937);  
Mattuch, Naturwiss 25, 189 (1937).
- (H90) Hibdon and Pool, Phys. Rev. 67, 313 (1945).
- (I1) Irvine, Jr., Phys. Rev. 55, 1105 (1939).
- (I2) Itoh, Proc. Phys. Math. Soc. Japan 23, 605 (1941).
- (I3) Itoh and Watase, Proc. Phys. Math. Soc. Japan 22, 784 (1940).
- (I4) Irvine, Jr., J. Phys. Chem. 46, 910 (1942).
- (J1) Jensen, Phys. Rev. 60, 430 (1941)
- (J4) Jaeckel, Zeits. f. Physik 110, 330 (1938).
- (J5) Joliet-Curie, I, Coliers Phys. No. 26 (1944).
- (K1) Knol and Veldkamf, Physica 3, 145 (1936).
- (K2) Krishnan, Nature 148, 407 (1941).
- (K3) King, Henderson, and Risser, Phys. Rev. 55, 1118 (1939).
- (K4) Kurie, Richardson, and Paxton, Phys. Rev. 49, 368 (1936).
- (K5) Kurtchatow, Kurchatow, Myssowsky, and Roussinow, Comptes Rendus 200, 1201 (1935).
- (K6) Kraus and Cork, Phys. Rev. 52, 763 (1937).
- (K7) Kurchatow, Latyschew, Nemenow, and Selinow, Physik. Zeits. Sowjetunion 8, 589 (1935).

- (K8) Kuerti and Van Voorhis, Phys. Rev. 56, 614 (1939).
- (K9) King and Henderson, Phys. Rev. 56, 1169 (1939).
- (K10) King and Elliott, Phys. Rev. 59, 108 (1941); 58, 846 (1940); 60, 489 (1941).
- (K11) Kennedy, Seaborg, and Segre, Phys. Rev. 56, 1095 (1939).
- (K12) Krishnan and Gant, Nature 144, 547 (1939).
- (K13) Kamen, Phys. Rev. 60, 537 (1941).
- (K14) Krishnan and Banks, Proc. Camb. Phil. Soc. 37, 317 (1941).
- (K15) Krishnan, Proc. Camb. Phil. Soc. 36, 500 (1940).
- (K16) Klaiber and Scharff-Goldhaber, Phys. Rev. 61, 733 (1942).
- (K17) Kent and Cork, Phys. Rev. 62, 297 (1942).
- (K18) Kennedy and Seaborg, Phys. Rev. 57, 843 (1940).
- (K19) Kurbatov, MacDonald, Pool, and Quill. Phys. Rev. 61, 106 (1942).
- (K20) Kurbatov, and Pool, Bull. Am. Phys. Soc. 18, No. 2, 9 (1943); Phys. Rev. 63, 463 (1943).
- (K21) Kurbatov, MacDonald, Pool, and Quill, Bull. Am. Phys. Soc. 16, No. 5, 8 (1941).
- (K22) Krishnan and Banks, Nature 145, 777 (1940).
- (K23) Krishnan and Gant, Nature 144, 547 (1939).
- (K24) Kamen and Ruben, Phys. Rev. 58, 194 (1940).
- (K25) Krishnan and Banks, Nature 145, 860 (1940).
- (K26) Kalbfell and Cooley, Phys. Rev. 58, 91 (1940).
- (K27) Krishnan and Nahum, Proc. Camb. Phil. Soc. 37, 422 (1941).
- (K28) Krishnan, Proc. Camb. Phil. Soc. 37, 186 (1941).
- (K29) Krishnan and Nahum, Proc. Camb. Phil. Soc. 36, 490 (1940).



- (K30) Kent, Cork, and Wadey, Phys. Rev. 61, 389 (1942).
- (K31) Krishnan and Banks, Proc. Camb. Phil. Soc. 37, 317 (1941).
- (K32) Konopinski and Uhlenbeck, Phys. Rev. 48, 7 (1935); see also Kurie, Richardson, and Paxton, Phys. Rev. 49, 368 (1936).
- (K33) Karlik and Bernert, Naturwiss. 31, 492 (1943).
- (K50) Kovarik and Adams, Phys. Rev. 54, 413 (1938).
- (K51) Karlik and Bernert, Naturwiss. 31, 298 (1943).
- (K52) Kolhorster, Naturwiss. 16, 28 (1928).
- (K53) Klemperer, Proc. Roy. Soc. London A148, 638 (1935).
- (K54) Kovarik and Adams, J. App. Phys. 12, 296 (1941).
- (K55) Kunder and Pool, Phys. Rev. 71, 467 (1947).
- 
- (L1) Lewis, Burcham, and Chang, Nature 139, 24 (1937).
- (L2) Langer and Stephens, Phys. Rev. 58, 759 (1940).
- (L3) Laslett, Phys. Rev. 52, 529 (1937).
- (L4) Lawrence, Phys. Rev. 47, 17 (1935).
- (L5) Lyman, Phys. Rev. 51, 1 (1937).
- (L6) Libby and Lee, Phys. Rev. 55, 245 (1939).
- (L7) Livingood and Seaborg, Phys. Rev. 54, 391 (1938).
- (L8) Livingood, Seaborg, and Fairbrother, Phys. Rev. 52, 135 (1937).
- 
- (L9) Livingood and Seaborg, Phys. Rev. 53, 847 (1938).
- (L10) Livingood and Seaborg, Phys. Rev. 60, 913 (1941).
- (L11) Livingood and Seaborg, Phys. Rev. 53, 765 (1938).
- (L12) Livingood and Seaborg, Phys. Rev. 55, 457 (1939).
- (L13) Livingood, Phys. Rev. 50, 425 (1936).
- (L14) Livingood and Seaborg, Phys. Rev. 54, 88 (1938).

- (L15) Lawson and Cork, Phys. Rev. 52, 531 (1937).
- (L16) Lark-Horovitz, Risser, and Smith, Phys. Rev. 55, 878 (1939).
- (L17) Livingood and Seaborg, Phys. Rev. 55, 667 (1939).
- (L18) Livingood and Seaborg, Phys. Rev. 55, 414 (1939).
- (L19) Livingood and Seaborg, Phys. Rev. 54, 775 (1938).
- (L20) Livingood and Seaborg, Phys. Rev. 54, 51 (1938).
- (L21) Lawson, Phys. Rev. 56, 131 (1939).
- (L22) Lyman, Phys. Rev. 55, 1123 (1939).
- (L23) Livingood and Seaborg, Phys. Rev. 55, 1268 (1939).
- (L24) Lawrence, Proc. Camb. Phil. Soc. 35, 304 (1939).
- (L25) Law, Pool, Kurbatov, and Quill, Phys. Rev. 59, 936 (1941).
- (L26) Lieber, Naturwiss. 27, 421 (1939).
- (L27) Langsdorf, Jr., Phys. Rev. 56, 205 (1939).
- (L28) Livingood and Seaborg, unpublished work.
- (L29) Lawson and Cork, Phys. Rev. 58, 580 (1940).
- (L30) Langsdorf, Jr., and Segre, Phys. Rev. 57, 105 (1940).
- (L31) Livingston and Wright, Phys. Rev. 56, 656 (1940).
- (L32) Lawson and Cork, Phys. Rev. 57, 356 (1940).
- (L33) Lutz, Pool, and Kurbatov, Bull. Am. Phys. Soc. 18, No. 6,  
6 (1943); Phys. Rev. 65, 61 (1944).
- (L48) Lawson, Phys. Rev. 57, 1082 (1940).
- (L57) Lawson and Cork, Phys. Rev. 57, 982 (1940).
- (L58) Levi, Nature 145, 588 (1940).
- (L60) Lichtblau, Naturwiss. 27, 260 (1939).
- (L70) Libby, Phys. Rev. 56, 21 (1939).
- (L71) Lecoin, J. de phys. et rad. 9, 81 (1938).
- (L72) Lee and Libby, Phys. Rev. 55, 252 (1939).
- (L73) Lewis and Bowden, Proc. Roy. Soc. London A145, 235 (1934).



Summarizes the results of various investigators. Values recalculated according to reference (H81).

- (L74) Libby and Latimer, J. Am. Chem. Soc. 55, 453 (1933).
- (L76) Langer, Phys. Rev. 51, 713 (1937).
- (L77) Levinger and Meiners, Phys. Rev. 71, 586 (1947).
  
- (M1) Maier, Leibnitz, Naturwiss. 26, 614 (1939).
- (M2) Mandeville, Phys. Rev. 62, 555 (1942).
- (M3) McMillan and Livingston, Phys. Rev. 47, 452 (1935).
- (M4) Magnan, Comptes rendus 205, 1147 (1937).
- (M5) McMillan and Lawrence, Phys. Rev. 47, 343 (1935).
- (M6) Mandeville, Phys. Rev. 63, 91 (1943).
- (M7) Mann, Phys. Rev. 52, 405 (1937).
- (M8) Mann, Phys. Rev. 54, 649 (1938).
- (M9) Moussa and Goldstein, Phys. Rev. 60, 534 (1941); Comptes rendus 212, 986 (1941).
- (M10) Mitchell, Phys. Rev. 51, 995 (1937).
- (M11) Mitchell and Langer, Phys. Rev. 53, 505 (1938).
- (M12) Mitchell, Phys. Rev. 53, 269 (1938).
- (M13) Marsh and Sugden, Nature 136, 102 (1935).
- (M14) McLennan, Grimmet, and Read, Nature 135, 147 (1935).
- (M15) McMillan, Kamen, and Ruben, Phys. Rev. 52, 375 (1937).
- (M16) McLennan, Grimmet, and Read, Nature 135, 505 (1935).
- (M17) Meitner, Strassmann, and Hahn, Zeits. f. Physik 109, 538 (1938).
- (M18) McLennan and Rann, Nature 136, 831 (1935).
- (M19) McMillan, Phys. Rev. 55, 510 (1939).

- (M21) McCreary, Kuerti, and Van Voorhis, Phys. Rev. 57, 351 (1940).
- (M22) McMillan, private communication.
- (M23) Minakawa, Phys. Rev. 60, 689 (1941).
- (M24) Mounce, Pool, and Kurbatov, Phys. Rev. 61, 389 (1942).
- (M25) Maurer and Ramm, Naturwiss. 29, 368 (1941).
- (M26) Magnan, Ann. d. Physik 15, 5 (1941).
- (M27) Mandeville, Phys. Rev. 63, 387 (1943).
- (M28) McMillan and Abelson, Phys. Rev. 57, 1185 (1940).
- (M29) Mackenzie, private communication.
- (M30) Mandeville, Phys. Rev. 64, 147 (1943).
- (M31) Meitner, Arkiv. f. Mat. Astron. Fysik A27, No. 17, 18 (1940).
- (M32) Maurer and Ramm, Zeits. f. Physik 119, 602 (1942).
- (M33) Moquin and Pool, Bull. Am. Phys. Soc. 18, No. 6, 6 (1943);  
Phys. Rev. 65, 60 (1944).
- (M34) Mandeville and Fulbright, Phys. Rev. 64, 265 (1943).
- (M35) Mitchell, Langer, and McDaniel, Phys. Rev. 57, 1107 (1940).
- (M36) Minakawa, Phys. Rev. 57, 1189 (1940).
- (M37) McMillan, Phys. Rev. 58, 178 (1940).
- (M38) Maurer and Ramm, Zeits. f. Physik 119, 334 (1942).
- (M50) Murphey, Phys. Rev. 59, 320 (1941).
- (M51) McKellar, Phys. Rev. 45, 761 (1934).
- (M52) Mitchell, Brown, and Fowler, Phys. Rev. 60, 359 (1941).
- (M53) Mattauch and Hauk, Naturwiss. 25, 781 (1937).
- (M54) Mattauch, Lichtblau, Schuler, and Gollnow, Zeits. f. Physik  
111, 514 (1939).



- (M55) Mattauch and Ewald, Naturwiss. 31, 487 (1943).
- (M60) Meitner, Zeits. f. Physik 17, 54 (1923).
- (M61) Marshall, Proc. Roy. Soc. London A173, 391 (1939).
- (M62) Meler and Curtiss, P. P. R. 9B, 745 (1946).
- (M63) Motta, Boyd, and Brosi, Phys. Rev. 71, 210 (1947).
- (M64) Mulner, Arkiv. Mat. Ast. Fysik. 6, (1945).
- 
- (N1) Nahmias and Walen, Comptes rendus 203, 71 (1936).
- (N2) Newson, Phys. Rev. 48, 790 (1935).
- (N3) Newson, Phys. Rev. 51, 624 (1937).
- (N4) Naidu and Siday, Proc. Phys. Soc. London 48, 332 (1936).
- (N5) Nishina, Yasaki, Kimura, and Ikawa, Nature 142, 874 (1938).
- (N6) Nielsen, Phys. Rev. 60, 160 (1941).
- (N7) Neuninger and Rona, Anz. Akad. Wiss. Wien, Math.-naturw. Klasse 73, 159 (1936).
- (N8) Nishina, Yasaki, Ezoe, Kimura, and Ikawa, Phys. Rev. 57, 1182 (1940).
- (N9) Nishina, Yasaki, Ezoe, Kimura, and Ikawa, Nature, 146, 24 (1940).
- (N10) Nelson, Pool, and Kurbatov, Phys. Rev. 61, 733 (1942); 62, 1 (1942).
- (N11) Nelson, Pool, and Kurbatov, Phys. Rev. 61, 428 (1942).
- (N12) Nishina, Yasaki, Kimura, and Ikawa, Phys. Rev. 59, 677 (1941).
- (N13) Nishina, Yasaki, Kimura, and Ikawa, Phys. Rev. 59, 323 (1941).
- (N14) Nishina, Yasaki, Kimura, and Ikawa, Phys. Rev. 58, 660 (1940).
- (N15) Nishina, Kimura, Yasaki, and Ikawa, Zeits. f. Physik 119, 195 (1942).
- (N30) Nier, Phys. Rev. 52, 933 (1937).

- (N31) Nier and Gulbranson, J. Am. Chem. Soc. 61, 697 (1939).
- (N32) Nier, Phys. Rev. 53, 383 (1938).
- (N33) Nier and Hanson, Phys. Rev. 50, 722 (1936).
- (N34) Nier, Phys. Rev. 50, 1041 (1936).
- (N35) Nier, Phys. Rev. 55, 1143 (1939).
- (N36) Nier, Phys. Rev. 54, 275 (1938).
- (N37) Nier, Phys. Rev. 52, 887 (1937).
- (N38) Nier, J. Am. Chem. Soc. 60, 1571 (1938).
- (N39) Nier, Phys. Rev. 55, 150 (1939).
- (N40) Neary, Proc. Roy. Soc. London A175, 71 (1940).
- (N41) Nier, Phys. Rev. 55, 150 (1939). Values recalculated according to reference (K54).
  
- (01) Oldenberg, Phys. Rev. 53, 35 (1938).
- (02) Oppenheimer and Tomlinson, Phys. Rev. 56, 858 (1939).
- (03) O'Neal, Phys. Rev. 60, 359 (1941).
- (04) O'Neal, and Goldhaber, Phys. Rev. 58, 574 (1940).
- (05) O'Neal, Phys. Rev. 59, 109 (1941).
- (06) O'Neal and Goldhaber, Phys. Rev. 57, 1086 (1940).
- (07) O'Connor, Pool, and Kurbatov, Phys. Rev. 62, 413 (1942).
- (08) O'Neal and Scharff-Goldhaber, Phys. Rev. 62, 83 (1942).
- (09) Ollano, Ricerca Scient. 11, 568 (1940).
- (010) Ogle and Kruger, Bull. Am. Phys. Soc. 18, No. 6, 6 (1943);  
Phys. Rev. 65, 61 (1944).
- (020) Ornstein and Vreeswijk, Zeits. f. Physik 80, 57 (1933).



- (O30) Ollano, Nuovo Cimento 18, 11 (1941).
- (P1) Polessitsky, Physik. Zeits. Sowjetunion 12, 339 (1937).
- (P2) Pool, Cork, and Thornton, Phys. Rev. 52, 239 (1937).
- (P3) Plesset, Phys. Rev. 62, 181 (1942).
- (P4) Perrier, Santangelo, and Segre, Phys. Rev. 53, 104 (1938).
- (P5) Pontecorvo, Phys. Rev. 54, 542 (1938).
- (P6) Pool, Phys. Rev. 53, 116 (1938).
- (P7) Pontecorvo and Lazard, Comptes rendus 208, 99 (1938).
- (P8) Pool and Cork, Phys. Rev. 51, 1010 (1937).
- (P9) Pool and Quill, Phys. Rev. 53, 437 (1938).
- (P10) Preiswek and von Halban, Comptes rendus 201, 722 (1935).
- (P11) Pecher, Phys. Rev. 58, 843 (1940).
- (P12) Polesitsky and Nemerovsky, Comptes rendus U.R.S.S. 28, 217 (1940).
- (P13) Perfilov, Comptes rendus U.R.S.S. 33, 485 (1941).
- (P14) Pool and Kurbatov, Bull. Am. Phys. Soc. 18, No. 2, 9 (1943); Phys. Rev. 63, 463 (1943).
- (P15) Polesitsky and Orbeli, Comptes rendus U.R.S.S. 28, 215 (1940).
- (P16) Polesitsky, Nemerovsky, Orbeli, and Baronckik, J. Phys. U.S.S.R. 4, 284 (1941).
- (P21) Pollard and Watson, Phys. Rev. 58, 12 (1940).
- (P40) Perey, Comptes rendus 208, 97 (1939); J. de phys. et rad. 10, 435 (1939).
- (P41) Perey and Lecoin, J. de Phys. et rad. 10, 439 (1939).

- (P42) Perey and Lecoin, Nature 144, 326 (1939).
- (P43) Perey and Lecoin, Comptes rendus 212, 893 (1941).
- (P44) Paul, Naturwiss. 31, 419 (1943).
- (P45) Pool and Edwards, Proc. Amer. Phys. Soc. (1945); Phys. Rev. 69, 140 (1946).
- (P46) Purlman, Seaborg, and Segre, Isotope Chart, May 1947.
- (R1) Roberts, Heydenburg, and Locher, Phys. Rev. 53, 1016 (1938).
- (R2) Richardson, Phys. Rev. 55, 609 (1939).
- (R3) Ridenour and Henderson, Phys. Rev. 52, 889 (1937).
- (R4) Richardson, Phys. Rev. 53, 124 (1938).
- (R5) Ridenour, Delsasso, White, and Sherr, Phys. Rev. 53, 770 (1938).
- (R6) Roberts, Downing, and Deutsch, Phys. Rev. 60, 544 (1941).
- (R7) Rotblat, Nature 148, 371 (1941).
- (R8) Richardson and Kurie, Phys. Rev. 50, 999 (1936).
- (R9) Risser, Phys. Rev. 52, 768 (1937).
- (R10) Reddemann and Strassmann, Naturwiss. 26, 187 (1938).
- (R11) Ruben and Kamen, private communication.
- (R12) Richardson, Phys. Rev. 60, 188 (1941).
- (R13) Rumbaugh, Roberts, and Hafstad, Phys. Rev. 54, 657 (1938).
- (R14) Rumbaugh and Hafstad, Phys. Rev. 50, 681 (1936).
- (R15) Reddemann, Naturwiss. 28, 110 (1940).
- (R16) Risser, Lark-Horovitz, and Smith, Phys. Rev. 57, 355 (1940).
- (R17) Ruben and Kamen, Phys. Rev. 57, 549 (1940).
- (R19) Roberts and Irvine, Phys. Rev. 59, 936 (1941).
- (R20) Reddemann, Zeits. f. Physik 116, 137 (1940).



- (R21) Ruben and Kamen, Phys. Rev. 59, 349 (1941).
- (R22) Riezler, Naturwiss. 31, 326 (1943).
- (R23) Roberts, Elliott, Downing, Peacock, and Deutsch, Phys. Rev. 64, 268 (1943).
- (R24) Rona, Anz. Akad. Wiss. Wien, Math.-naturw. Klasse 73, 159 (1936).
- (R40) Rasetti, Elements of Nuclear Physics (Prentice-Hall Inc., New York, 1936).
- (R41) Rotblat, Proc. Roy. Soc. London A177, 260 (1941).
- (R42) Ringo, Phys. Rev. 58, 942 (1940); 59, 107 (1941). Value recalculated according to (H81).
- (R43) Rayton and Wilkins, Phys. Rev. 51, 818 (1937). Values recalculated according to reference (H81).
- (R44) Roll and Wilkinson, Phys. Rev. 71, 321 (1947).
- (R45) Reid, Dunning, Weinhouse, and Grosse, Phys. Rev. 70, 431 (1946).
  
- (S1) Snell, Phys. Rev. 51, 143 (1937).
- (S2) Sagane, Phys. Rev. 50, 1141 (1936).
- (S3) Snell, Phys. Rev. 49, 555 (1936).
- (S4) Segre, Phys. Rev. 55, 1105 (1939).
- (S5) Sinma and Yamasaki, Sci. Papers Inst. Phys. Chem. Research Tokyo 35, 16 (1938).
- (S6) Sagane, Phys. Rev. 55, 31 (1939).
- (S7) Sagane, Phys. Rev. 53, 212 (1938).
- (S8) Solomon, Phys. Rev. 60, 279 (1941).

- (S9) Snell, Phys. Rev. 52, 1007 (1937).
- (S10) Segre, Halford, and Seaborg, Phys. Rev. 55, 321 (1939).
- (S11) Stewart, Lawson, and Cork, Phys. Rev. 52, 901 (1937).
- (S12) Sagane, Kojima, Miyamoto, and Ikawa, Phys. Rev. 54, 543 (1938).
- (S13) Sagane, Kojima, Miyamoto, and Ikawa, Phys. Rev. 54, 970 (1938).
- (S14) Seaborg and Segre, Phys. Rev. 55, 808 (1939).
- (S15) Seaborg, Livingood, and Kennedy, Phys. Rev. 57, 363 (1940).
- (S16) Sinma and Yamasaki, Phys. Rev. 55, 320 (1939).
- (S17) Sizoo and Eijkman, Physica 6, 332 (1939).
- (S18) Strain, Phys. Rev. 54, 1021 (1938).
- (S19) Smith, Phys. Rev. 61, 578 (1942).
- (S20) Scheichenberger, Anz. Akad. Wiss. Wien, Math.-naturw. Klasse 75, 108 (1938).
- (S21) Segre and Wu, Phys. Rev. 57, 552 (1940).
- (S22) Segre, Kennedy, and Seaborg, unpublished work.
- (S23) Shaeffer and Harteck, Zeits. f. Physik 113, 287 (1939).
- (S24) Stewart, Phys. Rev. 56, 629 (1939).
- (S25) Sagane, Kojima, and Miyamoto, Proc. Phys. Math. Soc. Japan 21, 728 (1939).
- (S26) Sagane, Kojima, Miyamoto, and Ikawa, Proc. Phys. Math. Soc. Japan 21, 660 (1939).
- (S27) Segre and Wu, private communication.
- (S29) Sagane, Miyamoto, and Ikawa, Phys. Rev. 59, 904 (1941).
- (S30) Seaborg, Livingood, and Friedlander, Phys. Rev. 59, 320 (1941).



- (S31) Siday, Proc. Roy. Soc. London A178, 189 (1941).
- (S32) Scharff-Goldhaber, Phys. Rev. 59, 937 (1941).
- (S33) Segre and Seaborg, Phys. Rev. 59, 212 (1941).
- (S34) Smith, Phys. Rev. 61, 389 (1942).
- (S35) Strassmann and Hahn, Naturwiss. 28, 817 (1940).
- (S36) Seaborg and Friedlander, Phys. Rev. 59, 400 (1941).
- (S37) Sherr, Bainbridge, and Anderson, Phys. Rev. 60, 473 (1941).
- (S38) Seaborg, Gofman, and Kennedy, Phys. Rev. 59, 321 (1941).
- (S39) Starke, Naturwiss. 30, 107 (1942).
- (S40) Sagane, Kojima, Miyamoto, and Ikawa, Phys. Rev. 57, 750 (1940).
- (S41) Seelmann-Eggebert, Naturwiss. 28, 451 (1940).
- (S42) Sagane, Kojima, Miyamoto, and Ikawa. Proc. Phys. Math. Soc. Japan 22, 174 (1940).
- (S43) Seelmann-Eggebert and Born, Naturwiss. 31, 59 (1943).
- (S44) Starke, Naturwiss. 30, 577 (1942).
- (S45) Sherr, Phys. Rev. 57, 937 (1940).
- (S46) Sagane, Kojima, Miyamoto, and Ikawa, Phys. Rev. 57, 1180 (1940).
- (S47) Seelmann-Eggebert, Naturwiss. 31, 491 (1943).
- (S48) Seelmann-Eggebert, Naturwiss. 31, 510 (1943).
- (S49) Siegbahn, Nature 153, 221 (1944).
- (S60) Smythe, Phys. Rev. 45, 299 (1934).
- (S61) Sampson and Bleakney, Phys. Rev. 50, 456 (1936).
- (S62) Smythe and Hemmendinger, Phys. Rev. 51, 178 (1937).

- (S63) Sampson and Bleakney, Phys. Rev. 50, 732 (1936).
- (S70) Sargent, Can. J. Research A17, 103 (1939).
- (S71) Sargent, Can. J. Research A17, 82 (1939); Phys. Rev. 54, 232 (1938).
- (S72) Sargent, Proc. Roy. Soc. London A139, 659 (1939).  
Summarizes the results of various investigators.
- (S73) Schintlmeister, Sitz. Akad. Wiss. Wien. Abt. IIa 146, 371 (1937).
- (S74) Strassmann and Walling, Ber. d. D. Chem. Ges. 71, 1 (1938).
- (S75) Sizoo and Wytzes, Physica 4, 791 (1937).
- (S76) Schmidt, Verh. d. Phys. Ges. Berlin 17 (February 14, 1898),  
and Wiedemann, Ann. d. Physik. u. Chemie 64, 720 (1898);  
65, 141 (1898).
- (S77) Schintlmeister and Lintner, Sitz. Akad. Wiss. Wien. Abt. IIa 148, 279 (1939).
- (S78) Siegbahn and Deutsch, Phys. Rev. 71, 483 (1947).
- (S79) Seren, Engelkemeir, Sturm, Friedlander, and Turkel, Phys. Rev. 71, 409 (1947).
- (S80) Siegbahn and Slotis, Arkiv. Mat., Ast. Fysik A32, 32 (1945).
- (S81) Sommers and Sherr, Phys. Rev. 69, 21 (1946).
- (S82) Seren, Moyer, Sturm, Phys. Rev. 70, 56 (1946).
- (S83) Schwarz and Pool, Phys. Rev. 71, 122 (1947).
- (S84) Swartout, Boyd, Cameron, Keim, and Larson, Phys. Rev., 70, 232 (1946).
- (S85) Siegbahn, and Kole, Phys. Rev., 70, 133 (1946).



- (S86) Siegbahn, Phys. Rev. 70, 127 (1946).
- (T1) Thornton, Phys. Rev. 51, 893 (1937).
- (T2) Thornton, Phys. Rev. 53, 326 (1938).
- (T3) Thornton, Phys. Rev. 49, 207 (1936).
- (T4) Tape and Cork, Phys. Rev. 53, 676 (1938).
- (T5) Thornton and Cork, Phys. Rev. 51, 383 (1937).
- (T6) Tyler, Phys. Rev. 56, 125 (1939).
- (T7) Tape, Phys. Rev. 56, 965 (1939).
- (T8) Townsend, Proc. Roy. Soc. London A177, 357 (1941).
- (T11) Townsend, Proc. Roy. Soc. London A175, S48 (1940).
- (T20) Tate and Smith, Phys. Rev. 43, 672 (1933).
- (T30) Thompson and Rowlands, Nature 152, 103 (1943).
- (T31) Thomson, Phil. Mag. [6] 10, 584 (1905).
  
- (V1) Van Voorhis, Phys. Rev. 49, 889 (1936).
- (V2) Van Voorhis, Phys. Rev. 50, 895 (1936).
- (V3) Valley and McCreary, Phys. Rev. 55, 666 (1939).
- (V4) Van Voorhis, private communication.
- (V5) Victorin, Proc. Camb. Phil. Soc. 34, 612 (1938).
- (V6) Valley, Phys. Rev. 59, 686 (1941).
- (V7) Valley and McCreary, Phys. Rev. 56, 863 (1939).
- (V8) Valley, Phys. Rev. 60, 167 (1941).
- (V20) Vaughan, Williams, and Tate, Phys. Rev. 46, 327 (1934).
- (V21) Valley, Phys. Rev. 59, 836 (1941).
- (V22) Valley, Phys. Rev. 57, 1058 (1940).
- (V23) Valley, Phys. Rev. 59, 686A (1941).

- (W1) Walke, Phys. Rev. 52, 663 (1937).
- (W2) Welles, Phys. Rev. 59, 679 (1941).
- (W3) Walke, Phys. Rev. 52, 400 (1937).
- (W4) Walke, Phys. Rev. 52, 777 (1937).
- (W5) Walke, Williams, and Evans, Proc. Roy. Soc. London A171, 360 (1939).
- (W6) Walke, Phys. Rev. 52, 669 (1937).
- (W7) White, Delsasso, Fox, and Creutz, Phys. Rev. 56, 512 (1939).
- (W8) Walke, private communication.
- (W9) Weil and Barkas, Phys. Rev. 56, 485 (1939).
- (W10) Walke, Phys. Rev. 57, 163 (1940).
- (W11) White, Creutz, Delsasso, and Wilson, Phys. Rev. 59, 63 (1941).
- (W12) Walke, Thompson, and Holt, Phys. Rev. 57, 177 (1940).
- (W13) Walke, Thompson, and Holt, Phys. Rev. 57, 171 (1940).
- (W14) Ward, Proc. Camb. Phil. Soc. 35, 523 (1939).
- (W15) Watase, Itoh, and Takeda, Proc. Phys. Math. Soc. Japan 22, 90 (1940).
- (W16) Watase and Itoh, Proc. Phys. Math. Soc. Japan 21, 626 (1939).
- (W17) Watase, Proc. Phys. Math. Soc. Japan 23, 618 (1941).
- (W18) Weimer, Kurbatov, and Pool, Phys. Rev. 60, 469 (1941).
- (W19) Weil, Phys. Rev. 62, 229 (1942).
- (W20) Weil, Phys. Rev. 60, 167 (1941).
- (W21) Wu, Phys. Rev. 58, 926 (1940).
- (W22) Weimer, Pool, and Kurbatov, Phys. Rev. 63, 59 (1943).
- (W23) Weimer, Pool, and Kurbatov, Phys. Rev. 63, 67 (1943).



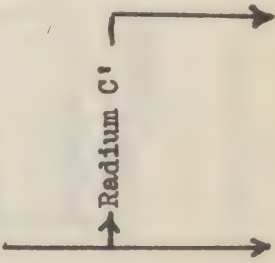
- (W24) Watson and Pollard, Phys. Rev. 57, 1082 (1940).
- (W25) Wu and Segre, Phys. Rev. 61, 203 (1942).
- (W26) Wu and Friedlander, Phys. Rev. 60, 747 (1941).
- (W27) Waldman and Collins, Phys. Rev. 57, 338 (1940).
- (W28) Weimer, Pool, and Kurbatov, Phys. Rev. 64, 43 (1943).
- (W29) Witcher, Phys. Rev. 60, 32 (1941).
- (W30) Wiedenbeck, Bull. Am. Phys. Soc. 19, No. 3, 5 (1944).
- (W40) Wilkins and Dempster, Phys. Rev. 54, 315 (1938).
- (W41) Wahl, Soc. Sci. fenn., Comment. physico-math. 11, 1 (1941).
- (W42) Wahl, Suomen Kemist. Tied. 50, 10 (1941).
- (W43) Wahl, Naturwiss. 29, 536 (1941).
- (W50) Ward, Proc. Roy. Soc. London A181, 183 (1942).
- (W51) Winand, J. de phys. et rad. 8, 429 (1937). Value recalculated to correspond to half-life of  $8.3 \times 10^4$  yr. for  $\text{I}_{10}$ .
- (W52) Wilkins and Crawford, Phys. Rev. 54, 316 (1938). Value recalculated according to reference (H81).
- (W53) Ward, Proc. Camb. Phil. Soc. 35, 322 (1939).
- (W54) Wiedenbeck, Phys. Rev. 68, 1 (1945).
- (W55) Wiedenbeck, Phys. Rev. 67, 53 (1945).
- (W56) Wiedenbeck, Phys. Rev. 68, 237 (1945).
- (W57) Wiedenbeck,
- (W58) Williams, D., Phys. Rev. 70, 983 (1946)
- (Y1) Yost, Ridenour, and Shinohara, J. Chem. Phys. 3, 133 (1935).
- (Y2) Yasaki and Watanabe, Nature 141, 787 (1938).

- (Y3) Yalow and Goldhaber, Bull. Am. Phys. Soc. 19, No. 3,  
5 (1944).
- (Y4) Yamasaki and Sinma, Sci. Papers Inst. Phys. Chem. Research  
Tokyo 37, 10 (1940).
- (Z1) Zlotowski and Williams, Phys. Rev. 62, 29 (1942).
- (Z2) Zumstein, Kurbatov, and Pool, Phys. Rev. 63, 59 (1943).
- (Z3) Zingg, Helv. Phys. Acta 13, 219 (1940).



TABLE 12 ALPHA PARTICLES FROM THE NATURAL RADIOACTIVE SERIES

Element	Atomic Wt	No	Half-life	Range cm in air	Energy mev	Vel X $3 \times 10^{10}$ cm sec	Distint Energy mev	Diff from Main Group X $10^5$ ev	Relat. Inten- sity
URANIUM AND RADIUM SERIES									
Uranium I	U1	238	92	4.55x10 <sup>9</sup> y	4.23	.0456	4.15	-	-
Uranium X <sub>1</sub>	U-X <sub>1</sub>	234	90	24. d	-	-	-	-	-
Uranium X <sub>2</sub>	U-X <sub>2</sub>	234	91	1.14 m	-	-	-	-	-
Uranium Z	UZ	234	91	6.7 h	-	-	-	-	-
Uranium II	U II	234	92	2.3x10 <sup>5</sup> y	4.76	.0479	4.7	-	-
Ionium	Io	230	90	8.2x10 <sup>4</sup> y	4.66	.0485	-	-	-
Radium	Ra	226	88	1600 y	4.791	.0500	-	-	-
Radon	Rn	222	86	3.823 d	5.4860	.0540	5.5886	-	-
Radium A	Ra-A	218	84	3.05 m	5.9981	.0565	6.1123	-	-
Radium B	Ra-B	214	82	26.8 m	-	-	-	-	-
Radium C	Ra-C	214	83	19.72 m	5.506	.0544	5.611	0	94
					5.445	.0539	5.549	.622	113
					7.6802	.064	7.829	0	10 <sup>6</sup>
					8.2769	.0665	8.437	6.08	0.43
					8.941	.0691	9.112	12.83	(.45)
					9.0655	.0696	9.241	14.12	22



→ Radium C' →

# ALPHA PARTICLES FROM THE NATURAL RADIOACTIVE SERIES

Element	Atomic Wt	Atomic No	Half-life	Range cm in air	Energy mev	Vel X 3 x 10 <sup>10</sup> cm sec	Distint Energy mev	Diff from Main Group X 10 <sup>5</sup> ev	Relate Inten- sity
→ Radium C' →	214	84	1.5x10 <sup>-4</sup> s	-	9.315	.0706	9.493	16.63	0.38
				9.724	9.4877	.0711	9.673	18.44	1.35
				-	9.660	.0718	9.844	20.15	0.35
				-	9.781	.0723	9.968	21.38	1.06
				-	9.908	.0728	10.097	22.68	0.36
				-	10.077	.0734	10.269	24.39	1.67
				-	10.149	.0736	10.342	25.13	0.38
				-	10.329	.0742	10.526	26.97	1.12
				11.51	10.5052	.0749	10.709	28.80	0.23
				11.580	10.5379				
→ Radium C'' →	210	81	1.32 m						
Radium D	210	82	22.2 y						
Radium E	210	83	4.975 d						
Radium F (Polonium)	210	84	139.5 d	3.845 (mean)	3.685		5.403	-	21
					3.890				18
					4.016				19
					4.111				48



ALPHA PARTICLES FROM THE NATURAL RADIOACTIVE SERIES

Element	Atomic Wt	No	Half-life	Range cm in air	Energy mev	Vel $\times 10^{10}$ cm sec	Distint Energy mev	Diff from Main Group $\times 10^5$ ev	Relat. Inten- sity
Radium F (Polonium)	210	84	139.5 d		4.303				43
					4.449				79
					4.640				70
					4.749				64
					4.838				49
					4.901				84
					5.065				(126)
					5.113				(96)
					5.2984	.0523			10 <sup>6</sup>
					5.303				
Radium G (Lead)	206	82	stable						

# ALPHA PARTICLES FROM THE NATURAL RADIOACTIVE SERIES

Element	Atomic Wt	No	Half-life	Range cm in air	Energy mev	Velx $3 \times 10^{10}$ cm sec	Distint Energy mev	Diff from Main Group $10^6$ ev	Relat. Inten- sity
ACTINIUM SERIES									
Actinium-Uranium	Ac-U	235 92	$7.07 \times 10^8$ y	-	4.52	-	-	-	-
Uranium Y	U-Y	231 90	24.64 h	3.20	4.69	-	4.77	-	-
Protoactinium	Pa	231 91	$3.2 \times 10^4$ y	3.23	4.72	-	4.80	-	-
				3.511	5.00	-	5.09	-	-
				-	5.0	-	-	-	-
Actinium	Ac	227 89	13.4 y	-	6.051	.0569	6.159	0	80
Radio Actinium	Rd-ac	227 90	18.9 d	(4.36)	6.019	.0567	6.127	.32	15
					5.990	.0566	6.097	.62	100
					5.968	.0565	6.075	.84	15
					5.924	.0563	6.030	1.29	5
					5.870	.0560	5.975	1.84	10
					5.817	.0557	5.921	2.38	5
					5.766	.0555	5.869	2.90	80
					5.744	.0554	5.847	3.12	15



# ALPHA PARTICLES FROM THE NATURAL RADIOACTIVE SERIES

Element	Atomic Wt	No	Half-life	Range cm in air	Energy mev	Vel X $3 \times 10^{10}$ cm sec	Distint Energy mev	Diff from Main Group X $10^5$ ev	Relat. Inten- sity
→ Radio Actinium	Rd-Ac	227	90	18.9 d	5.719	.0553	5.822	3.37	60
→ Actinium K	Ac-K	223	87	21.0 m	5.674	.0550	5.776	3.83	10
Actinium X	Ac-X	223	88	11.2 d	-	-	-	-	-
Actinon	An	219	86	3.92 s	5.719	.0552	5.823	0	6
				(4.17)	5.607	.0547	5.709	1.14	4
					5.533	.0544	5.634	1.89	1
				5.692	6.8235	.0603	6.953	0	10
				5.240	6.561	.0592	6.683	2.70	1
				5.14	6.436	.0586	6.556	3.97	1
Actinium A	Ac-A	215	84	$1.83 \times 10^{-3}$ s	7.365	.0627	-	-	-
Actinium B	Ac-B	211	82	36.0 m	6.618	.0594	6.739	0	100
Actinium C	Ac-C	211	83	2.16 m	6.272	.0578	6.383	3.56	19
Actinium C'	Ac-C'	211	84	$2.0 \times 10^{-3}$ s	7.680	.0630	-	-	-
Actinium C''	Ac-C''	207	81	4.71 m					
Actinium D (Lead)	Ac-D (Pb)	207	82	stable					

Element	Atomic Wt	No	Half-life	Range cm in air	Energy mev	Vel X $3 \times 10^{10}$ cm sec	Distint Energy mev	Diff from Main Group $\times 10^5$ ev	Relat. Inten- sity
THORIUM SERIES									
Thorium	Th	232	90	1.389x10 <sup>10</sup> y	4.20	.0481	4.34	-	-
Mesothorium 1	MsTh1	228	88	6.7 y					
Mesothorium 2	MsTh2	228	89	6.13 h					
Radiothorium	RdTh	228	90	1.90 y	5.420	(.0527)	5.517	0	5
					5.335	-	5.431	.80	1
Thorium X	ThX	224	88	3.64 d	5.6825	.0546	5.7858	-	-
Thoron	Th	220	86	54.50 s	6.2813	.0579	6.399	-	-
Thorium A	Th-A	216	84	0.145 s	6.7744	.0602	6.903	-	-
Thorium B	Th-B	212	82	10.6 h					
Thorium C	Th-C	212	83	60.6 m	6.083	.0570	6.200	0	27.2
					6.044	.0535	6.160	.4	69.8
				(4.730) mean	5.762	.0555	5.872	3.278	1.8
					5.620	.0548	5.728	4.724	.16
					5.601	.0544	5.708	4.918	1.10
→ Thorium C'	Th-C'	212	84	3x10 <sup>-7</sup> s	8.7759	.0684	8.947	0	10 <sup>6</sup>
				9.687	9.491	.0712	9.673	7.26	34



# ALPHA PARTICLES FROM THE NATURAL RADIOACTIVE SERIES

Element	Atomic Wt	No	Half-life	Range cm in air	Energy mev	Vel $\times 10^{10}$ cm sec	Distint Energy mev	Diff from Main Group $\times 10^5$ ev	Relat. Inten- sity
Thorium C'	212	84	$3 \times 10^{-7}$ s	11.543	10.541	.0750	10.744	17.97	190
Thorium C''	208	81	3.1 m	-	-	-	-	-	-
Thorium D (Lead)	208	82	stable	-	-	-	-	-	-

Table 13. "NEPTUNIUM" SERIES

Recent evidence has been presented for the existence of a fourth natural radioactive series of the form  $(4n + 1)$ . Its probable members and arrangement is given below as reported (1,2). The name "Neptunium Series" after the longest lived member was proposed in accordance with the practice for naming the other three series (1,2).

Element		Atomic No.	Wt.	Half-life	Rad.	Alpha-energy mev	Beta-energy mev
Plutonium	Pu	94	241		$\beta^-$		
Americium	Am	95	241	500 y	$\alpha$		
Neptunium	Np	93	237	$2.25 \times 10^6$ y	$\alpha$		
Protoactinium	Pa	91	233	27.4 d	$\beta^-$		0.4
Uranium	U	92	233	$1.63 \times 10^5$ y	$\alpha$	$4.825 \pm .003$	
Thorium	Th	90	229	$5 \times 10^3$ y	$\alpha$	$\sim 5$	
Radium	Ra	88	225	14 d	$\beta^-$		<0.05
Actinium	Ac	89	225	10 d	$\alpha$	$5.801 \pm .010$	
Francium	Fa	87	221	5 m	$\alpha$	$6.31 \pm .02$	
Astatine	At	85	217	$2.1 \times 10^{-2}$ s	$\alpha$	$7.023 \pm .010$	
Bismuth	Bi	83	213	46 m	$\alpha$ 2% $\beta$ 98%	$5.86 \pm .03$	$\sim 1.3$
Polonium	Po	84	213	$3.2 \times 10^{-6}$ s	$\alpha$	$8.336 \pm .005$	
(Thallium)	Tl	81	209				
Lead	Pb	82	209	3.3 h	$\beta$		0.70
Bismuth	Bi	83	209	stable			

1. Hageman, F., Katzin, L. I., Studier, M. H., Ghiorso, A., and Seaborg, G. T., Phys. Rev., 72, 253 (1947).
2. English, A. C., Cranshaw, T. E., Demers, P., Harvey, J. A., Hink, E. P., Jelley, J. V., and May, A. N., Phys. Rev., 72, 253 (1947).





## 12. RADIOACTIVE DECAY

### A. Law of Radioactive Decay

Radioactive decay is a statistical process following well established rules. A single radioactive nucleus, i.e., excited nucleus, possesses a fixed probability of disintegration per unit time which is characteristic of the particular isotope and its state of excitation. Aside from these two factors, the probability of decay and, hence, the rate of decay of a macroscopic quantity of the radioisotope is wholly independent of external influences such as temperature, pressure, chemical reagents, and the means by which it is produced. Since each disintegration is a statistically independent event, the average number of nuclei which disintegrate per unit time is proportional to the number of nuclei of the particular species and state of excitation present at any instant:

$$\frac{dN}{dt} = -\lambda N$$

$N$  = number of nuclei present at time

$\lambda$  = disintegration constant; factor of proportionality characteristic of the isotope and its state of excitation.

The quantity,  $N$ , is frequently given any convenient dimension and may be referred to as the number of nuclei, activity, mass, or some wholly arbitrary unit.



## B. Fluctuations

The actual number of disintegrations observed per unit time fluctuates about a mean value,  $N$ , as a consequence of the random character of the disintegration process. The probability of observing  $M$  events per unit time when the average value is  $N$ , is given by Poisson probability distribution formula:

$$P_M = \frac{N^M}{M!} e^{-N}$$

When the average value,  $N$ , is large and the difference  $N-M$  is small, the probability distribution is given approximately by Gauss' formula:

$$P_M = \frac{1}{\sqrt{2\pi N}} e^{-\frac{(M-N)^2}{2N}}$$

An estimate of the statistical error in the measurement of an activity  $N$  is expressed in terms of the absolute probable error given by:

$$r = 0.6745 \sqrt{N}$$

or in terms of the percent probable error by:

$$r\% = 67.45 \frac{1}{\sqrt{N}}$$

## C. Simple Decay

The decay of a given quantity of radioisotope follows a simple exponential law provided it is not at the same time being produced by some agency.

If  $N_0$  is the initial number of atoms of the isotope, the number of atoms remaining after a time,  $t$ , is:

$$N = N_0 e^{-\lambda t}$$

$$\lambda = \text{decay constant (t}^{-1}\text{)}$$

However, the decay of an isotope is usually expressed in terms of half-life,  $T$ , which is the time required for the number of radioactive atoms to be reduced by one half. The number of atoms present at time,  $t$ , is then:

$$N = N_0 e^{-0.693 \frac{t}{T}}$$

Also frequently used is the mean life,  $\tau = T/0.693 = 1/\lambda$  which is the time required for an initial quantity of radioisotope to be reduced by  $1/e$ . The activity of any substance as a function of the number of half-lives is plotted in figure 83.

#### D. Growth of Radioactivity

When a radioisotope is produced at a constant rate, e.g., in a cyclotron or from uranium, the number of atoms of the product radioisotope after a time,  $t$ , is:

$$N = N_0 (1 - e^{-0.693 \frac{t}{T}})$$

$N_0$  = saturation activity; i.e., activity at which rate of production of the isotope equals rate of its decay.  
 = rate of formation divided by  $\lambda$ .



#### E. Radioactive Substance Produced by Parent of Long Half-life

When a radioactive daughter substance is produced, for which the half-life,  $T_2$  is short compared to the radioactive parent, i.e.,  $T_1 \gg T_2$ , the initial quantity of the daughter substance after time,  $t$ , is:

$$N_2 = N_0 \frac{T_2}{T_1} \left( 1 - e^{-0.693 \frac{t}{T_2}} \right)$$

where  $N_0$  is the initial quantity of the parent. After many half-lives of the daughter, the parent and daughter are in secular equilibrium and the decay of the latter is governed now by the decay of the parent. The quantity of the daughter is then proportional to the ratio of their half-lives:

$$N_2 = N_0 \frac{T_2}{T_1}$$

This mode of radioactive decay is shown in figure 85. The area under both curves must be equal since the same number of atoms are involved in the complete decay of parent and daughter.

#### F. Parent and Daughter Substances of Comparable Half-life

When half-lives of parent and daughter are of the same order of magnitudes and only the parent is present initially, the activity of the daughter substance at any later time is given by:

$$N_2 = \frac{T_2}{T_1 - T_2} N_0 e^{-0.693 \left( e^{-\frac{t}{T_1}} - e^{-\frac{t}{T_2}} \right)}$$

The activity of the daughter increases to a maximum and then decays after a sufficiently long time at a rate corresponding to the longer of the two half-lives. The ratio of daughter to parent substance in transient equilibrium is:

$$N_2 = \frac{T_2}{T_2 - T_1} N_0$$

#### G. Decay of nth Component in a Radioactive Chain

If a given initial quantity,  $N_0$ , of radioisotope decays in a series of radioactive daughter substances, the quantity of the  $n$ th successive daughter substance after a time,  $t$ , is given by (1):

$$N = N_0 \left( a_1 e^{-0.693 \frac{t}{T_1}} + a_2 e^{-0.693 \frac{t}{T_2}} + \dots + a_n e^{-0.693 \frac{t}{T_n}} \right)$$

$$a_1 = \frac{T_1^{n-1}}{(T_1 - T_2)(T_1 - T_3) \dots (T_1 - T_n)}$$

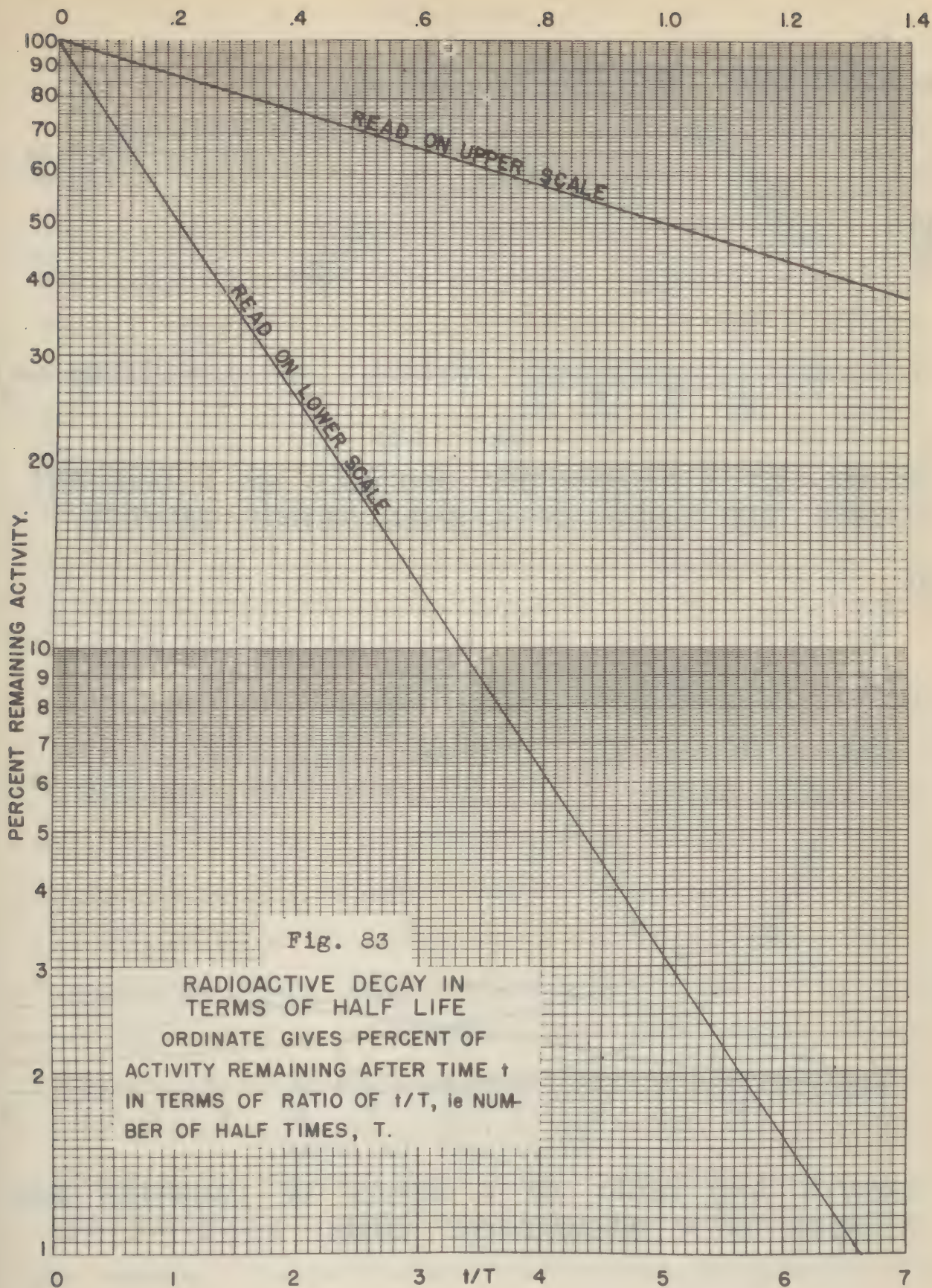
$$a_2 = \frac{T_2^{n-1}}{(T_2 - T_1)(T_2 - T_3) \dots (T_2 - T_n)}$$

$$a_n = \frac{T_n^{n-1}}{(T_n - T_1)(T_n - T_2) \dots (T_n - T_{n-1})}$$

$T_1, T_2 \dots T_n$  = half-lives of parent and successive daughter substances

1. Bateman, Proc. Camb. Phil. Soc. 15, 423 (1910)





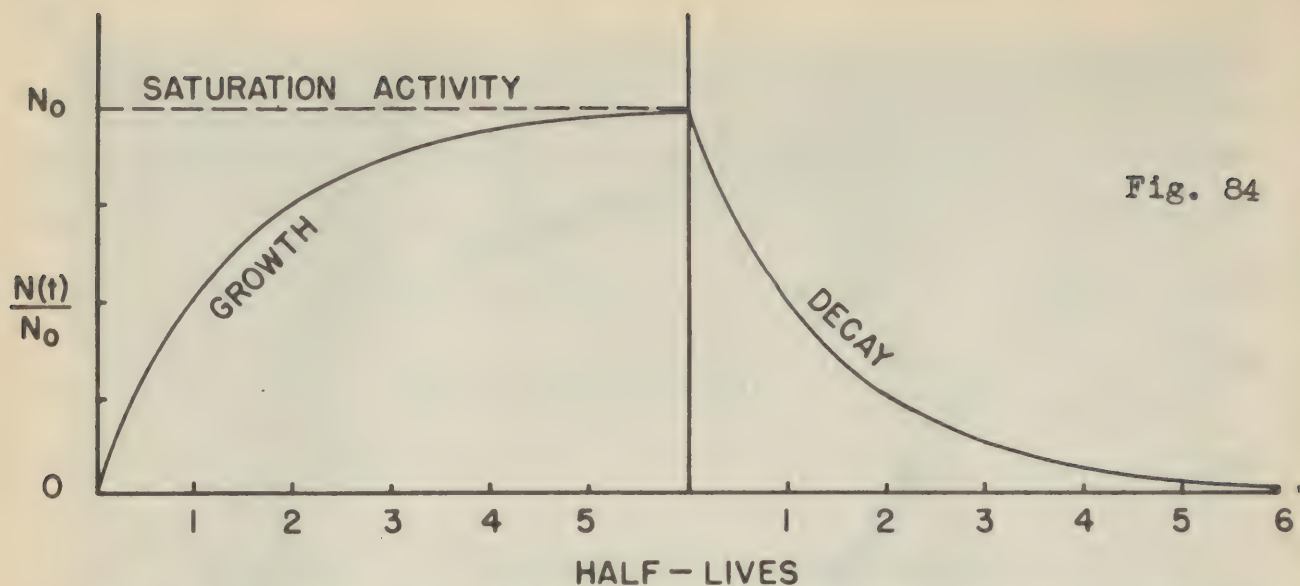


Fig. 84

GROWTH OF A RADIOISOTOPE PRODUCED BY A CONSTANT SOURCE AND DECAY OF A GIVEN INITIAL QUANTITY.

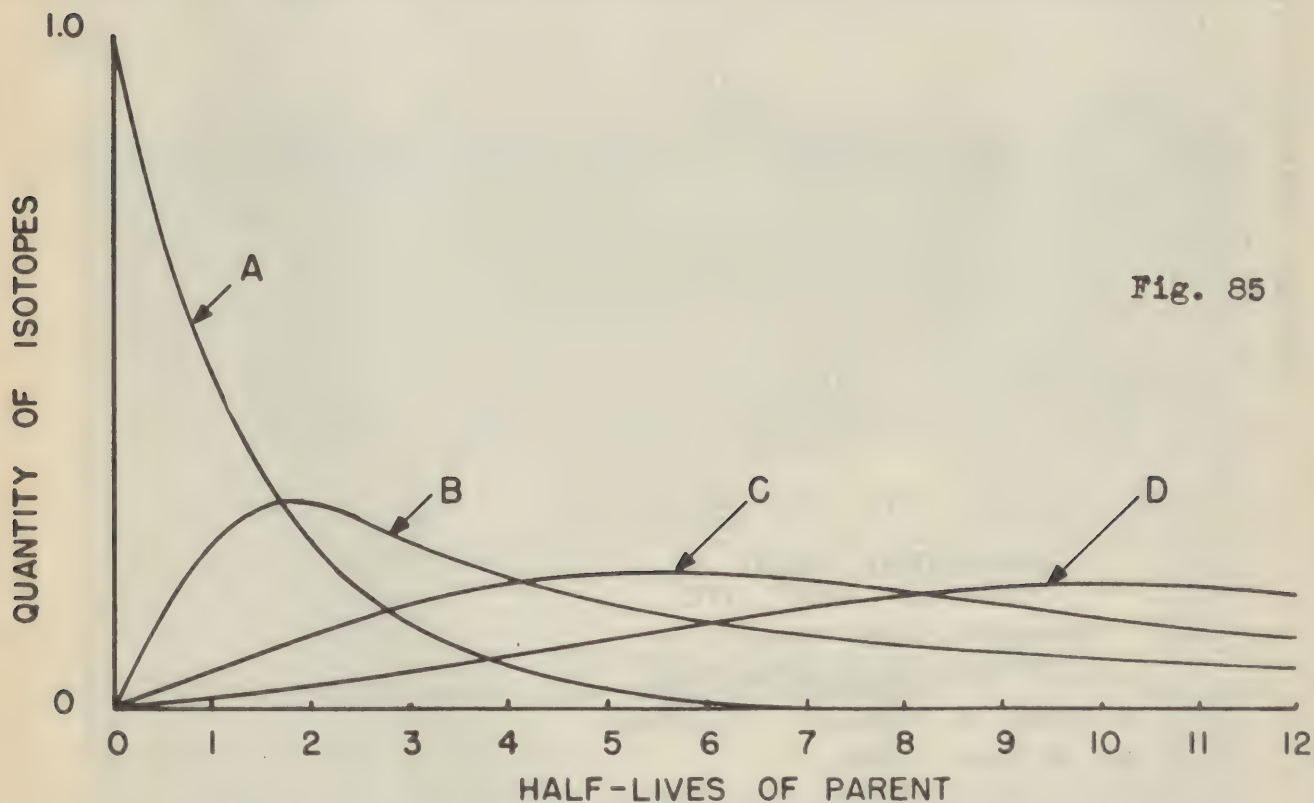


Fig. 85

GROWTH AND DECAY OF A SERIES OF DAUGHTER SUBSTANCES IN A RADIOACTIVE CHAIN  $A \rightarrow B \rightarrow C \rightarrow D$ .



## 13. FISSION

### A. Mechanism of Fission

The discovery by Hahn and Stassmann (1) that elements of medium atomic weight were formed from uranium bombarded with neutrons came as the culmination of an unexplained phenomenon encountered in the investigations of Fermi, Meitner, Hahn, Strassmann, Curie, and Savitch. Meitner and Frisch (2) named the process "fission" in analogy to the rupture of a sphere of incompressible fluid as a result of deformation. The analogy of the "liquid drop" had already been applied in principle to heavy nuclei by Bohr and Kalckar (3) and the general theory of liquid sphere dynamics had been developed in detail for its application to stellar dynamics. Following the discovery of fission, Bohr and Wheeler (4) extended the liquid drop analogy into a theory of fission with marked success in its agreement with the observations of the details of fission processes.

In heavy nuclei, the aggregate of elementary particles form the equivalent to a spherical drop of incompressible liquid with a volume proportional to the number of particles,  $V = \frac{4}{3} \pi r_0^3 A$ , and an effective surface tension,  $\tau$ , arising from the short range attractive fields between the particles, (n, n), (p,p) and (n,p). The surface tension is compensated, in part, by the repulsive electrostatic field of the uniform distribution of proton charge  $eZ$  throughout the nucleus. Under the influence of an external force, the nucleus may be excited into one of many possible modes of vibration producing deformations in the spherical form similar to the corresponding vibrations of a liquid sphere. The stability of the drop to these small deformations depends upon the relative strengths of the surface tension and the counter-acting electrostatic field. As the total number of particles in stable nuclei increases, a limiting size is attained for which the compensation of the

cohesive nuclear force by the electrostatic field is complete and the drop is then unstable to spontaneous fission. Nuclei only slightly smaller than the limiting size, although exceedingly stable against spontaneous fission, will divide when sufficiently excited. A small deformation accompanying excitation allows a redistribution of charge to the surface regions of smaller curvature, thus giving the repulsive field an advantage over the surface tension. A sufficiently large deformation, therefore, leads to complete division and the separated charged fragments recoil, because of their similar charges, with an energy of the order of 200 mev. The high excitation energy of the fragments following fission is subsequently lost by the emission of prompt (instantaneous) neutrons and gamma rays and through radioactive chains leading finally to known stable nuclei.

### B. Fission Probability

#### 1. Qualitative features.

The probability of fission depends, first, on the probability of neutron capture to form an excited compound nucleus and, second, on the relative probabilities for de-excitation of the compound nucleus by radiation, neutron emission, and fission.

Both the neutron binding energy and critical energy for fission in heavy nuclei lie in the energy range 5-7 mev. When the neutron binding energy plus its kinetic energy is less than the critical energy, radiation and neutron emission are more probable than fission. Conversely, the radiation probability is negligible compared to fission and neutron emission for excitation energies greater than the critical energy for fission. Thus, thermal neutrons induce fission in the nuclei U235 and Pu239 with greater probability



than radiation since the neutron binding energies of 5.4 and 6.4 mev are greater than the respective critical energies of 5.2 and 5 mev. On the other hand, the probability of fission in U238 and Th232 becomes important only for fast neutrons since the critical energies are of the order of 1 mev greater than the neutron binding energy. In general, the fission barrier height in the heaviest nuclei with odd atomic weight is lower than the neutron binding energy, thus allowing fission to be induced by thermal neutrons.

## 2. Cross sections.

The absolute values of the probabilities for radiative capture, neutron emission and fission in terms of their cross sections can be estimated by applying the dispersion theory (4,5,6) and using the widths for these processes calculated by Bohr and Wheeler (1) summarized below.

a. Neutron emission width for process which leaves the nucleus in the ground state (Identical to width for neutron capture and excitation to the same levels):

$$\Gamma_{n'} = \sum_J (\Gamma_{n'})_J (2J+1) = (2s+1)(2i+1) \frac{R^2 d}{2\pi \chi^2}$$

$i$  = spin of initial nucleus.

$J$  = spin of compound nucleus.

$s$  = neutron spin (1/2).

$d$  = average spacing of levels with a given angular momentum.

$R$  = nuclear radius =  $1.48 \times 10^{-13} A^{1/3} = r_0 A^{1/3}$ .

b. Fission width:

$$\Gamma_f = \frac{Nd}{2\pi}$$

$N$  = number of energy levels available for a given  
excitation energy ( in the order of ten ).

c. Neutron emission width for a process leaving the residual nucleus in any excited state.

$$\Gamma_n = \frac{d}{2\pi} \frac{8 \pi^2 m r_0^2 A^{2/3}}{h^2} (E - E_n - \sum_1 E_1)$$

$E$  = excitation energy.

$E_n$  = neutron binding energy.

$E_1$  = energy of available state,  $i$ , in residual  
nucleus for a given excitation energy.

The neutron width equals  $\Gamma_n$  for energies less than the order of 100 kev but at energies greater than this  $\Gamma_n > \Gamma_n'$ . The radiation width is essentially constant for states of excitation due to neutron capture, i.e.,  $> 5$  mev, and is of the order of magnitude of 1 mev.

d. Total width.

$$\Gamma = \Gamma_n + \Gamma_r + \Gamma_f$$

3. Resonance.

When the spacing between levels,  $d$ , is greater than the level widths, only a single level may be important. For an incident neutron energy  $E$  near a resonance energy  $E_0$ , the cross section for radiation and fission are given by the one-level formula (5):

$$\sigma_r = \pi \lambda^2 \frac{2J+1}{(2s+1)(2i+1)} \frac{\Gamma_n' \Gamma_r}{(E - E_0)^2 + (\Gamma/2)^2}$$

$$\sigma_f = \pi \lambda^2 \frac{2J+1}{(2s+1)(2i+1)} \frac{\Gamma_n' \Gamma_r}{(E - E_0)^2 + (\Gamma/2)^2}$$



At excitation energies of 5-7 mev, corresponding to the binding energy of a neutron in a massive nucleus, the level spacing has already diminished to approximately 20 ev. The one-level resonance formulae, therefore, are valid only for slow or thermal neutrons since the excitation contributed by the combined kinetic and binding energies of fast neutrons lies in a higher region of closely spaced levels and, hence, more than one level will be affected. In general, resonance capture of slow or thermal neutrons by nuclei of even atomic weight leads to de-excitation by radiation and neutron emission, and in nuclei of odd atomic weight the same process leads to fission and neutron emission.

#### 4. Non-resonance process

For excitation energies in the range for which the level spacing is of the order of, or less than, the total width, the one level formula is not valid since many levels then contribute to a nuclear process. As shown by Bohr, Peierls and Placzek, the cross sections are then given by:

a.  $\lambda \gg r_0 A^{1/3}$  (slow neutrons)

$$\sigma_f = \pi \chi^2 \Gamma_n' \frac{\Gamma_f}{\Gamma} \frac{2\pi}{d}$$

$$\sigma_r = \pi \chi^2 \Gamma_n' \frac{\Gamma_r}{\Gamma} \frac{2\pi}{d}$$

b.  $\lambda < r_0 A^{1/3}$  (fast neutrons)

$$\sigma_f = \pi r_0^2 A^{2/3} \frac{\Gamma_f}{\Gamma}$$

$$\sigma_r = \pi r_0^2 A^{2/3} \frac{\Gamma_r}{\Gamma}$$

The fission cross section is small compared to radiative capture and neutron emission across sections in the energy range where the total excitation energy contributed by an incident neutron is less than the fission

barrier. When the fission barrier is exceeded, the fission cross section increased rapidly and the radiative capture cross section remains constant but becomes negligible by comparison. The neutron emission probability, on the other hand, remains an important competitive process for all excitation energies greater than the neutron binding energy.

At least for U235, the fission cross section in the slow neutron range varies as  $1/v$ , with a value of roughly 500 barns in the  $kT$  region (0.029 ev)

### C. Stability of Heavy Nuclei

The stability of heavy nuclei against fission depends upon the relative magnitudes of the short range nuclear forces (n,n), (p,p) and (n,p) responsible for an effective surface tension and the repulsive electrostatic field of the protons. Since the volume of the nucleus is proportional to the number of neutrons it contains (7), the energy associated with the short range forces maintaining a stable spherical nucleus is proportional to the nuclear surface:  $4\pi R^2 \sim A^{2/3}$ . Counteracting this, the uniform distribution of charge  $eZ$  gives rise to an electrostatic energy proportional to  $Z^2 A^{1/3}$  which therefore, increases more rapidly with nuclear size than the nuclear forces. A critical value of the ratio of the two fields expressed by  $Z^2 (A^{1/3}/A^{2/3}) = Z^2/A$ , is attained for increasing nuclear size when the electrostatic field exceeds the nuclear binding forces and the nucleus is no longer stable against spontaneous fission. A semi-empirical calculation by Bohr and Wheeler (4) lead to a critical value of  $Z^2/A = 47.8$ .

Nuclei with  $Z^2/A$  only slightly smaller ( $\sim 15\%$ ) than the critical value exhibit a marked stability against spontaneous fission when unexcited but division becomes highly probable for small deformations in the spherical form induced by external excitation. Classically, the minimum, or critical, excitation energy required to induce fission is equivalent to the height of the



potential, or fission, barrier formed by the difference of the attractive nuclear field and repulsive electrostatic field. Alternatively, it is the energy necessary to induce a deformation of a liquid drop for which the cohesive forces become less than the repulsive forces within the drop. Effectively, the height of the barrier decreases with increasing value of  $Z^2/A$  and when  $Z^2/A = 47.8$ , the fission barrier vanishes entirely.

For nuclei with  $Z^2/A$  near the limiting value, the critical excitation energy for fission can be obtained from the expression derived by Bohr and Wheeler (2).

$$E_f = 4\pi r_0^2 \tau A^{2/3} \left[ \frac{98}{135} (1-x)^3 - \frac{11,368}{34,425} (1-x)^4 + \dots \right]$$

$$x = \frac{Z^2/A}{(Z^2/A)_{\text{lim.}}} = Z^2/47.8 A$$

$$4\pi r_0^2 \tau = 14 \text{ mev}$$

$$r_0 = 1.47 \times 10^{-13} \text{ (4,8)}$$

Spontaneous fission is possible but relatively improbable in unexcited nuclei and in nuclei with less than the critical excitation energy. The rate of fission is then given by the probability of penetration of the fragments through the potential barrier, which decreases rapidly with increasing barrier height and width. The half-life of heavy nuclei for fission from the ground appears to be of the order of  $10^{17} - 10^{22}$  years.

#### D. Energy Relations

##### 1. Neutron binding energy.

An estimation of the neutron binding energy in heavy nuclei is important for a determination of the neutron kinetic energy necessary to induce fission. For nuclei greater than  $A = 250$ , the neutron binding energy has a

value between 5 and 7 mev. On capture of a neutron, this energy plus the neutron kinetic energy is contributed to excitation of the compound nucleus. From the relation  $Mc^2 = E$ , the binding energy,  $E_n$ , can be calculated from the mass difference of the initial and compound nuclei:

$$E_n = 931 (M_A + M_{A+1} + n)$$

The masses  $M$  are calculated from the semi-empirical relation (9) ( see:

Binding Energy ):

$$M_A = 1.00893 (A - Z) + 1.00812 Z - 0.00504 A \\ + 0.014 A^{2/3} + 0.000627 Z^2 A^{-1/3} \\ + 0.083 \left( Z - \frac{A}{2} \right)^2 A^{-1} + \left\{ \begin{array}{l} 0, A \text{ odd} \\ + \\ - \end{array} \right\} 0.036 A^{-3/4} \left\{ \begin{array}{l} A \text{ even}, Z \text{ odd} \\ A \text{ even}, Z \text{ even} \end{array} \right\}$$

The physical significance of the seven terms in their respective order is

1. Total free mass of neutrons.
2. Total free mass of proton plus  $Z$  electrons (i.e.  $Z$  hydrogen atoms)
3. Correction for mass defect per particle based on empirical mass curves.
4. Correction for smaller binding energy of particles at surface compared to inner particles.
5. Correction for partial compensation of binding between protons due to uniformly distributed charge  $eZ$ .
6. Correction in the 1st order of approximation for the excess of neutrons over the number of protons.
7. Empirical correction for odd and even compositions of protons and neutrons.



## 2. Fission energy

The energy released in fission can be estimated from either the electrostatic repulsion of the two product nuclei or from the difference in mass between the compound nucleus and the fission products.

The first method provides only a rough approximation. Assuming the fission particles to spheres with charges  $Z_1$  and  $Z_2$  and initially in contact, the repulsive energy, from electrostatic theory is

$$E_f = \frac{e^2 Z_1 Z_2}{1.47 \times 10^{-13} (A_1^{1/3} + A_2^{1/3})} \quad \text{ergs.}$$

The fission energy calculated by this is approximately 200 mev.

The second method provides a more accurate estimate of the fission energy. The total energy released, including the excitation energy of the fission products as well as their kinetic energy, is given the energy equivalent of the difference in mass between the initial, unexcited nucleus,  $M$ , and the unexcited fission products at rest,  $M_i$ :

$$E_f = 931 (M + n - \sum_i M_i) + E_n' + E_{n,\gamma}$$

where all  $M$ 's are in units of mass ( $0.16/16 = 1.00000$ ). The separate masses can be calculated with the aid of the formula given in the preceding section. The summation is taken over the rest masses of all prompt and delayed neutrons as well as the two heavy particles.  $E_n'$  is the initial neutron kinetic energy and  $E_{n,\gamma}$  is the energy carried off by all neutrons (K.E.).

## 3. Distribution of fission energy

The greater portion of the total energy release associated with fission, and the only energy released directly by the process, appears as kinetic energy of the fragments. Measurements of the total recoil energy (10) gives

a value of approximately 160 mev which is shared by the two fragments inversely as their respective masses, i.e.,  $E_1/E_2 = M_2/M_1$ . In addition to the kinetic energy, the fragments carry off an excitation energy of approximately 40 mev. This is subsequently lost by neutron emission (prompt and delayed), 10 mev; prompt gamma radiation, 15 mev; and radioactive chains leading to stable nuclei by beta, neutrino, gamma and delayed neutron emission, 20 mev. The energy loss through each of the processes in the radioactive chain correspond to discrete level transitions; in many cases, identical with previously established activities. The energy contributed to prompt neutron and gamma emission exhibits a continuous distribution which is observed to be superimposed on that of the fission fragment which seems to indicate that such particles are emitted from the fragments following the main fission process. The fact that the energy distribution is continuous arises from the great density of closely spaced energy levels at high excitation energies which present an essentially continuous set of possible transitions of the nucleus to lower states by neutron and gamma emission. Occasionally, alpha particles are emitted with an observed maximum energy of 16 mev (11).

## E. Fission Products

### 1. Fission fragments

The distribution of the atomic masses of fission fragments exhibits a marked asymmetry about a value of one-half the atomic mass of the fission nucleus. Fragments of nearly equal mass occur with relatively little probability and for U235 the most probable masses are those near 95 and 140. The total range of U235 fragments includes masses from 70 to 160 as shown in figure (87) and table 14. No wholly adequate theory has been provided thus far to account for the form of the asymmetric yield distribution.



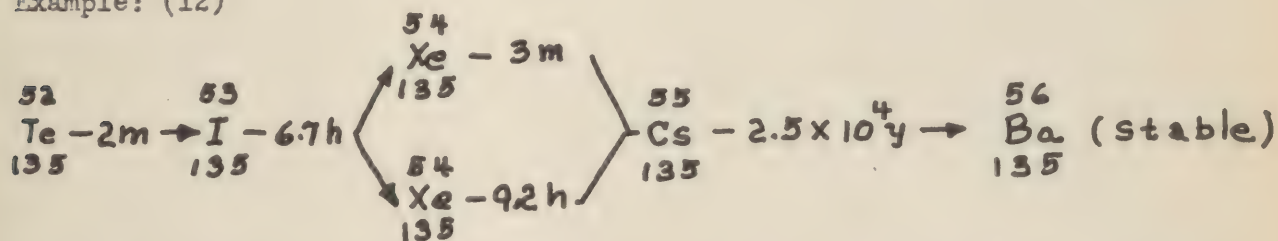
## 2. Prompt neutrons and gamma rays

Part of the high excitation energy of the fission fragments is lost by neutron and gamma emission immediately following fission. Referred to as prompt neutrons and gamma rays, they are observed to occur simultaneously with fission but probably are not associated with the primary fission process. On the average, between two and three prompt neutrons accompany each fission event.

## 3. Radioactive chains

The remaining excitation energy of the fission fragments after prompt neutron and gamma emission is subsequently lost by delayed neutron, beta, neutrino, and gamma emission. The initial fragments formed contain an excess of neutrons compared to existing stable isotopes. By successive beta decay and occasional delayed neutron emission, the fragments are enabled by these radioactive chains to terminate in known stable and unexcited isotopic species.

Example: (12)



On the average each fragment undergoes three beta transformations accompanied by characteristic isomeric transitions. Many of the resulting activities observed correspond to earlier known activities produced by other processes. The number of delayed neutrons observed to occur in the chain activities is very small compared to the number of prompt neutrons; approximately 1.0 percent.

The half-times for delayed neutrons varies from approximately 0.5 sec. to 0.5 min. and gamma rays are observed with the same period indicating an alternative mode of de-excitation by isomeric transition for this step in the

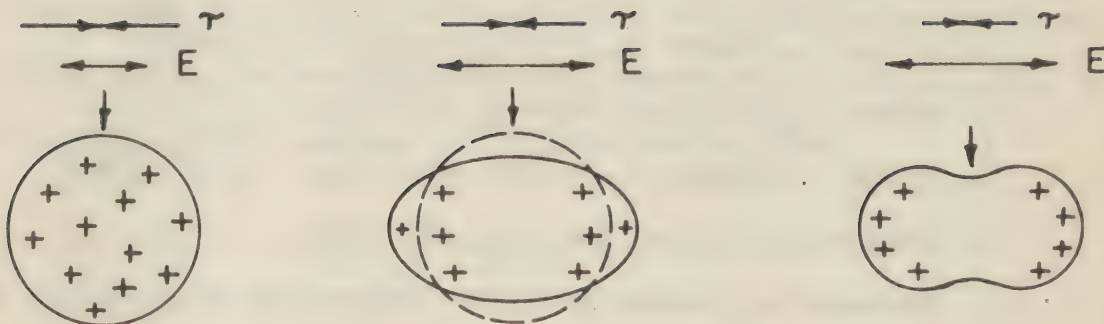
process.

#### 4. Alpha particles.

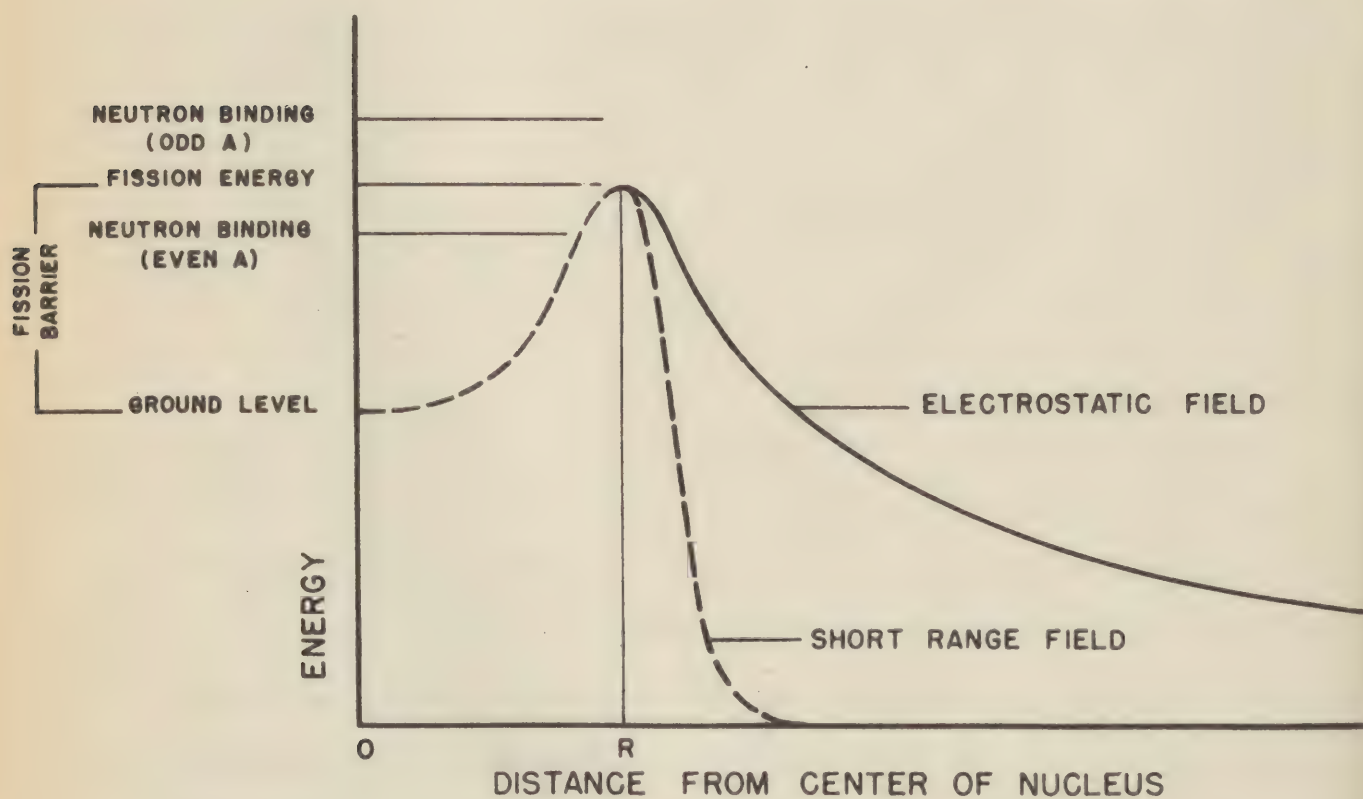
Alpha particles have been found to be emitted by both U235 and Pu239 within  $5 \times 10^{-6}$  sec. after the primary fission process (11). The maximum observed energy is 16 mev and the frequency of occurrence appears to be 1 alpha particle per 250 fissions in U235 and one per 500 fissions in Pu239.



1. Mahn, O., Strassman, F., Naturwiss, 27, 11 (1939).
2. Meitner, L., Frisch, O.R., Nature, 143, 239 (1939).
3. Bohr, N., Kalckar, Kyl., Dansh. Acad. (139).
4. Bohr, N., Wheeler, J.A., Phys. Rev. 56, 426 (1939).
5. Breit, G., Wigner, E., Phys. Rev. 49, 519 (1936).
6. Bethe, H., Rev. Mod. Phys. 9, 69 (1937).
7. Bethe, H., Bacher, R.F., Rev. Mod. Phys. 8, 32 (1937).
8. Feenberg, E., Phys. Rev. 55, 504 (1939).
9. Deutsch, M., Seminar in Nuclear Science and Engr., M.I.T. (1946).
10. Jentacke, Zeits. f. Physik, 120, 165 (1943).
11. Farwell, G., Segre', E., Wiegand, C., Phys. Rev. 71, 327 (1947).
12. Plutonium Project, J., Am. Chem. Soc. 68, 2411 (1946).



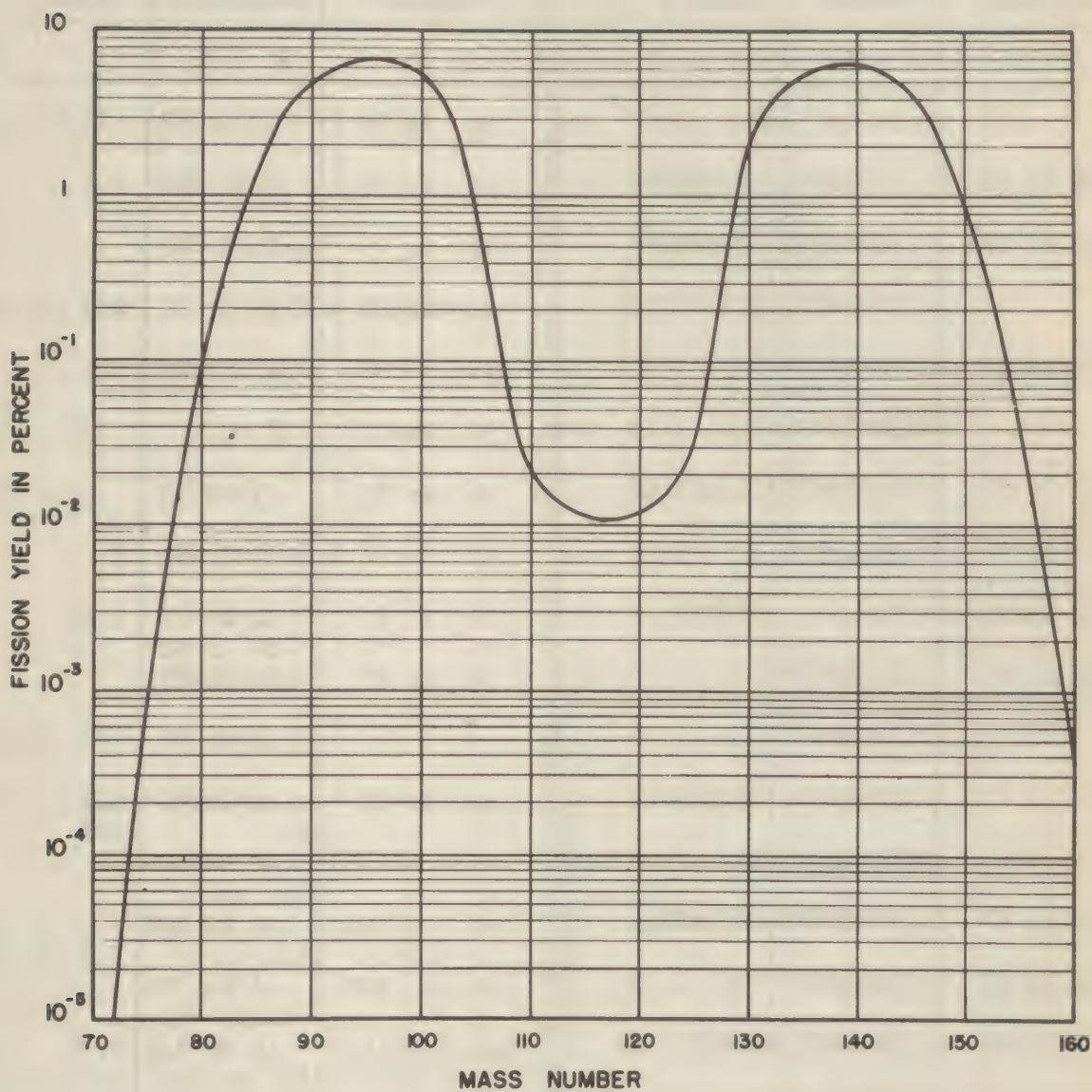
DEFORMATION OF CHARGED LIQUID DROP LEADING TO FISSION



DIAGRAMMATIC REPRESENTATION OF NUCLEAR FIELDS

Fig. 86





YIELDS OF  $U^{235}$  FISSION PRODUCT CHAINS AS A FUNCTION OF MASS.

PLUTONIUM PROJECT, J.A.C.S., 68, 2437 (1946)

Fig. 87

# 14. TABLE OF FISSION YIELDS

Reprinted from the Plutonium Project Table, J. A. C. S.  
68 2411-2442 (1946)

Probable Fission Fragment			Stable Product			Fission Yield %	Probable Fission Fragment			Stable Product			Fission Yield %
Z	El	A	Z	El	A		Z	El	A	Z	El	A	
			31 Ga 71				36 Kr 88			38 Sr 88			
30 Zn 72			32 Ge 72			$1.5 \times 10^{-5}$	36 Kr 89			39 Y 89			4.6
30 En 73			32 Ge 73			$1.0 \times 10^{-4}$	36 Kr 90			40 Zr 90			
			32 Ge 74				36 Kr 91			40 Zr 91			9.5
32 Ge 75			33 As 75				37 Rb 92			40 Zr 92			5.1
			32 Ge 76				37 Rb ..			? .			
32 Ge 77			34 Se 77			0.0091	36 Kr 93			41 Cd 93			
33 As 78			34 Se 78				36 Kr 94			40 Zr 94			5
32 Ge 78			?			0.02	39 Y 95			42 Mo 95			6.4
34 Se 79			35 Br 79				36 Kr 97			40 Zr 96			
			34 Se 80							42 Mo 97			
33 As 81			35 Br 81			0.125	42 Mo 99			42 Mo 98			
			34 Se 82							44 Ru 99			6.2
35 Br 82			36 Kr 82			$2.8 \times 10^{-5}$	42 Mo 101			42 Mo 100			
34 Se 83			36 Kr 83				42 Mo 102			44 Ru 101			
34 Se 84			36 Kr 84			0.65	44 Ru 103			44 Ru 102			
35 Br 85			37 Rb 85							45 Rh 103			3.7
			36 Kr 86				42 Mo 105			44 Ru 104			
37 Rb 86			38 Sr 86			$2 \times 10^{-5}$	44 Ru 106			46 Pd 105			0.9
35 Br 87			36 Kr 87			0.026	43 Tc 107			46 Pd 106			0.5
35 Br 87			38 Sr 87							47 Ag 107			
										46 Pd 108			



Probable Fission Fragment	Stable Product	Fission Yield %	Probable Fission Fragment	Stable Product	Fission Yield %
Z El A	Z El A		Z El A	Z El A	
45 Rh 109	47 Ag 109	0.028	51 Sb 129	54 Xe 129	
	46 Pd 110			52 Te 130	
46 Pd 111	48 Cd 111	0.018	52 Te 131	54 Xe 131	2.8
46 Pd 112	48 Cd 112	0.011	51 Sb 132	54 Xe 132	3.6
	48 Cd 113		51 Sb 133	55 Cs 133	4.5
	48 Cd 114		51 Sb 134	54 Xe 134	5.7
48 Cd 115	49 In 115	0.0008	52 Te 135	56 Ba 135	5.9
	48 Cd 116		53 I 136	56 Ba 136	0.01
48 Cd 117	50 Sn 117	0.01	53 I 137	54 Xe 136	
48 Cd ..	48 Cd ..		53 I 137	56 Ba 137	
	50 Sn 118		54 Xe 138	56 Ba 138	
	50 Sn 119		54 Xe 139	57 La 139	6.3
	50 Sn 120		54 Xe 140	58 Ce 140	6.1
50 Sn 121	51 Sb 121	0.014	54 Xe 141	59 Pr 141	5.7
50 Sn 121 123	51 Sb 121 123	0.0012	55 Cs 142	58 Ce 142	
	50 Sn 122		54 Xe 143	60 Nd 143	5.4
50 Sn 123	51 Sb 123	0.0044	54 Xe 144	60 Nd 144	5.3
	50 Sn 124		54 Xe 145	60 Nd 145	
50 Sn 125	52 Te 125	0.023	58 Ce 146	60 Nd 146	
50 Sn 125	?		60 Nd 147	62 Sm 147	2.6
50 Sn 126	52 Te 126	0.1		60 Nd 148	
51 Sb 127	53 I 127		60 Nd 149	62 Sm 149	1.4
	52 Te 128			60 Nd 150	
			60 Nd 151	63 Eu 151	

Probable Fission Fragment	Stable Product	Fission Yield %
Z El A	Z El A	
	62 Sm 152	
61 153	63 Eu 153	0.15
	62 Sm 154	
62 Sm 155	64 Gd 155	0.03
61 156	64 Gd 156	0.013
63 Eu 157	64 Gd 157	0.0074
63 Eu 158	64 Gd 158	0.002



#### 14. ELECTROSTATIC GENERATOR

The most successful form of electrostatic generator for the acceleration of heavy charged particles is that first proposed by Van de Graaf (1). High potentials are produced by the accumulation of charge on the surface of large closed-surface conductors, usually spheres, called terminals. An endless belt of insulating material running from a position of ground potential to the interior of the terminal is sprayed with charge at the ground end, and conveyed to the interior of the terminal where it is removed by a collecting comb. The charge collected appears then only at the surface of the terminal leaving the interior a field-free region as required by elementary electrostatics. Ions formed by a source within the terminal are accelerated through a vacuum tube running from the terminal to the ground or to another terminal of opposite polarity. The maximum energy imparted to a particle is  $eV$ , or in terms of electron volts,  $nV$ ; the order of ionization of the particle times the potential difference between terminals. This places a severe limit on the energies derivable from such machines as compared to resonance and induction accelerators. The maximum voltage is established when the rate of charge leakage by corona discharge from the terminal equals the transport of charge by the belt. In the largest unit thus far built, this potential has exceeded 5 million volts between two terminals oppositely charged (2). Spun aluminum spheres 15 feet in diameter were used for terminals in this machine.

A typical belt charging system is shown in figure 88. To achieve the highest equilibrium voltage requires the greatest practicable charge transport; belts are operated at saturation charge, made as wide as the design permits, and operated at the highest practicable speed - usually several thousand feet per minute. Paper belts proved to be more practicable

in large installations than were silk, rayon, or linen; partly because of considerably lower cost but also because of desirable electrical properties (1,3). Charge is sprayed on the belt by a spray wire stretched across the belt near the pulley and at a distance of approximately one half inch, and charged to a potential ranging from 5 to 20 KV as determined by the desired equilibrium voltage on the terminal. Charge conveyed to the terminal is then removed with an efficiency of 35 to 60% by a collector comb consisting of a metal strip, containing numerous sharp points directed toward the belt, near the terminal pulley. Charge of opposite sign is sprayed on the belt in the terminal and again removed at the ground end, thus doubling the terminal charging rate. The current delivered to the belt by a charging system has been shown to be given by (1)

$$I = k(V - V_0)^2$$

$k$  = empirical constant.

$V$  = spray wire voltage.

$V_0$  = spray wire threshold.

The threshold voltage for sharp pointed combs is zero; for wires of small diameter, it is usually several kilovolts.

The vacuum accelerating tube is constructed of a series of insulating sections made of glass, pyrex, or porcelain which are separated by metallic rings and vacuum sealed. The metal rings support external corona rings to ensure uniform potential distribution along the length of the tube, and internal drift tubes through which the ion beam passes.

The drift tubes are essential for their focusing effect on the beam in order to compensate the defocusing effects of the initial angular divergence of ions leaving the ion source, space charge spreading, and scattering



by residual gas in the accelerating tube. The focusing arises from the form of the electric field in the gap between two successive drift tubes. As shown in figure 88, the field in the first half of the gap tends to deflect all ions toward the tube axis. Although the effect in the second half of the gap is reversed, due to symmetry of the field, the ions have gained axial momentum and the angle by which they are deflected from their path is then smaller than the initial focusing effect. The net effect, therefore, is to maintain a small pencil of ions which emerges over a small area at the target.

The general structural feature of this type of accelerator requires a high order of insulation shielding, and good geometrical form to reduce heavy charge loss by excessive corona discharge and sparking. Most such generators have been constructed in spherical form from aluminum sheet; spun or otherwise fabricated to the desired shape. Insulation is usually provided by mounting the terminal on sufficiently long tubes of herkolite, textolite, or other non-conducting materials which can be fabricated in large structural form. Power for operating the ion source and auxiliary equipment in the terminal is derived from a generator mounted in the terminal and driven by the charging belt or an auxiliary belt.

When possible, humidity control is provided in the space occupied by the charging belt. Humidity of less than 50% is generally necessary for consistent and optimum operation.

An important improvement in the design and operation of the electrostatic generator was introduced by enclosing the entire unit in an atmosphere of air, nitrogen,  $\text{CCl}_4$  or  $\text{CCl}_2\text{F}_2$  at high pressure. The chief advantage lies in the greater insulator strength of gases at pressures above atmospheric with a corresponding decrease in the breakdown gap for a particular voltage. This permits a very considerable reduction in the physical

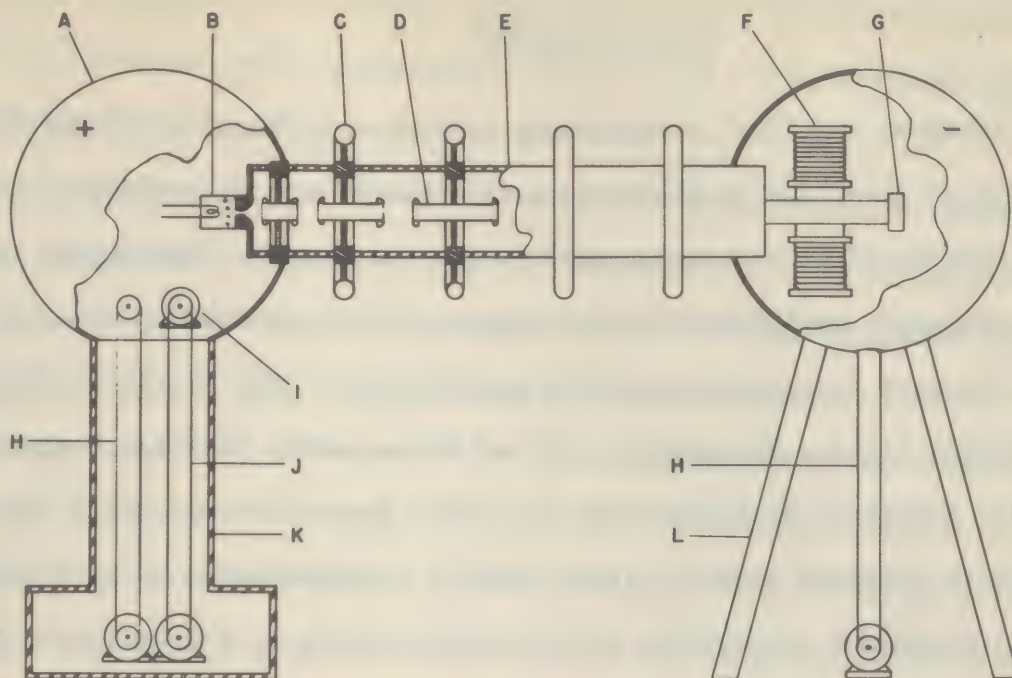
dimensions, which becomes important for high voltage installations. It allows, in addition, rigid control of the atmosphere and in particular, the humidity. The essential features of a high pressure electrostatic generator are the same as in the units operated at atmospheric pressure. They are however built compactly and enclosed in a steel tank designed to withstand a pressure of 10 atmospheres or more. Because of the small spacing between the terminal, accelerating tube, and the grounded tank wall, it is necessary to shield the entire unit with closely spaced hoops of aluminum tubing to insure a uniform potential distribution and to reduce sparking to the tank wall.

The acceleration of protons and alpha particles in an accelerator of this type does not provide strictly homogeneous beams of particles. Hydrogen introduced into the ionization chamber is injected into the acceleration tube both as  $H^+$  and  $H_2^+$ . Both particles reach the target with the same kinetic energy but the molecular ion splits into two  $H^+$  particles on impact, resulting in two particles, each with only half the original energy. Similarly, when accelerating alpha particles, both  $He^+$  and  $He^{++}$  may be produced by the source. Energetically homogeneous beams can be obtained readily, however, by passing the accelerated beam through a magnetic field or analyser before reaching the target to separate the particles  $H^+$  and  $H_2^+$  or  $He^+$  and  $He^{++}$ .

#### References

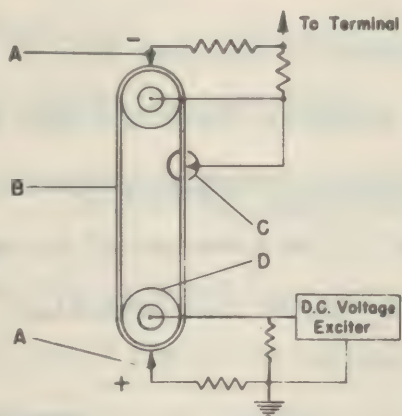
1. Van de Graaf, Compton, K. T., and Van Atta, L. C., Phys. Rev. 49, 761 (1936)
2. Van Atta, L. C., Northrup, D. L., Van Atta, C. M., and Van de Graaf, R. J., Phys. Rev. 49, 761 (1936)
3. Tuve, M. A., Hafstad, L. R., and Dahl, O., Phys. Rev. 48, 315 (1935)





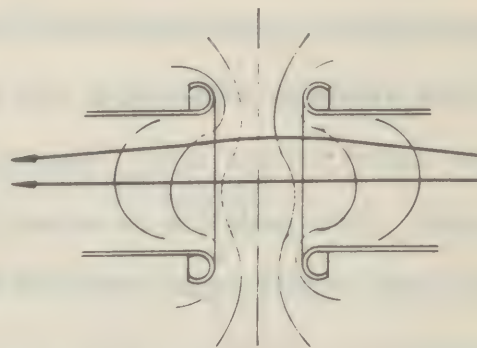
- A. TERMINAL: ALUMINUM SHELL
- B. ION SOURCE: FILAMENT, GRID, AND CAPILLARY CATHODE THROUGH WHICH IONS PASS INTO ACCELERATING TUBE
- C. CORONA RING
- D. DRIFT TUBE
- E. ACCELERATING TUBE INSULATOR SECTION
- F. ELECTROMAGNET FOR MAGNETIC SEPARATION OF BEAMS
- G. TARGET
- H. CHARGE BELT
- I. POWER GENERATOR FOR SOURCE AND OTHER EQUIPMENT
- J. AUXILIARY BELT FOR DRIVING POWER GENERATOR
- K. CYLINDRICAL TYPE SUPPORT INSULATOR
- L. TRIPOD TYPE SUPPORT INSULATOR

#### VAN DE GRAAFF ELECTROSTATIC GENERATOR



- A. SPRAY COMBS
- B. CHARGING BELT
- C. COLLECTOR AND SHIELD
- D. METALLIC PULLEY

#### CHARGING SYSTEM FOR ELECTROSTATIC GENERATOR



#### ELECTROSTATIC FOCUSING BETWEEN DRIFT TUBES

Fig. 88

## 15. BETATRON

### A. Description

The betatron was first successfully developed by Kirst (1,2) for the acceleration of electrons by electromagnetic induction. In principle, it is similar in operation to the common shell type transformer. Instead of employing a secondary coil however, electrons are injected into an evacuated "doughnut" to move freely in a circular path to which they are constrained by the magnetic field. The greater part of the magnetic flux loops through the circular orbits by an arrangement of narrow gaps and iron cores. Thus a tangentially directed induced electric field is experienced by an electron in an orbit of radius  $r$  identical to the field induced in a secondary winding.

$$E = \frac{1}{2\pi r C} \frac{d\Phi}{dt}$$

$C$  = velocity of light.

$\Phi$  = magnetic flux through the circular orbit.

The magnetic field,  $H$ , at the orbit increases at the same rate as the flux. If both the electron momentum,  $p$ , and the magnetic field increase in proportion, the radius of the orbit remains constant during the interval it is accelerated. The condition necessary for the maintenance of an equilibrium orbit of fixed radius  $r_0$  is given by the betatron flux condition

$$\Phi - \Phi_0 = 2\pi r_0^2 H$$

$\Phi_0$  = initial flux when  $H = 0$ .

$\Phi$  = flux at any instant.

$H$  = magnetic field at equilibrium orbit at same instant.



The flux through the orbit, therefore, must be proportional to twice the field strength at the orbit. Since both the linking flux and the magnetic field at the orbit are produced in the same gap by a single magnet, this condition is easily realized in practice.

Acceleration of the electrons from the initial injection energy to the maximum energy occurs in one quarter of the magnetic field cycle, either when the field is increasing, or decreasing. In either case the direction of rotation is reversed. The low frequency alternating magnetic field is produced by coils wound on the upper and lower pole pieces and, in the most efficient form, are coupled to a bank of condensers of appropriate capacity to form a resonant circuit. A generator is coupled to the circuit through a secondary winding to compensate for losses in the iron and for ohmic resistance.

A structure of laminated transformer iron is required for the yoke and pole pieces to reduce excessive heating and losses by induced eddy currents. Similarly, large metallic parts cannot be used in or near the region of gap. Eddy currents induced in conductors in this region cause sufficient alteration in the magnetic field to disturb the electron beam. The vacuum chamber or doughnut, therefore, is constructed wholly of non-conductive materials such as glass, quartz, or porcelain.

#### B. Electron Injection and Beam Extraction

Electrons are injected into the accelerating region from a source which is pulsed for a few micro-seconds at the proper instant in the magnetic field cycle. Normally the electrons are given an energy of 20 to 70 kev by electrostatic acceleration in the injector in order to provide electrons with a velocity near that of light. A comparatively simple source is used consisting of a hot cathode to emit electrons and a slit through which a narrow beam is accelerated as shown in figure 89 .

Several possible mechanisms have been proposed for extraction of the beam when the maximum energy is attained. In all cases, the beam is deflected from the equilibrium radius either to smaller radii where it ultimately impinges on a tungsten target to be converted into x-radiation or deflected to larger radii to strike a target mounted on the injector. The simplest scheme requires saturation of the pole pieces just before the maximum flux through the orbit is reached. The flux conditions is then no longer maintained; the electrons gain momentum faster than the magnetic field at the orbit increases and hence, spiral outward until they strike the tungsten target mounted on the back of the injector.

A second, and more practicable method of beam extraction alters the flux condition, by the use of auxillary coils at the pole pieces, at the end of the first quarter cycle of the magnetic field (3). These coils are energized by the discharge from a condenser bank and, depending upon the polarity, the field at the equilibrium orbit is increased or decreased while the linkage flux is little altered. The electrons, correspondingly spiral inward or outward to reach the target.

### C. Orbital Oscillations

The existence of an equilibrium orbit when the flux condition is maintained allows for stable oscillation about this orbit. If the magnetic field is radially symmetric, the principal oscillations are vertical and radial. As shown by Kerst and Serber (4), such oscillations will have frequencies given by

$$\begin{aligned}\Omega_{(\text{vert})} &= n^{\frac{1}{2}}\omega \\ \Omega_{(\text{rad})} &= (1-n)^{\frac{1}{2}}\omega \\ n &= \frac{d(\ln H)}{d(\ln r)}\end{aligned}$$

$\omega$  = angular velocity of electrons in equilibrium orbit.



Excitation of these modes of vibration accompanies injection as a result of the angular spread in the injected electrons and the displacement of the injector from the equilibrium orbit. Electrons leaving the injector must spiral inward to approach the stable orbit whose radius satisfies the flux condition; but, depending upon the initial angle of injection, the electron may overshoot or undershoot the equilibrium orbit and subsequently oscillate with simple harmonic motion about the correct radius and the median plane with a frequency usually less than that of rotation. Further excitation of these oscillations may occur during acceleration both from the effect of space charge spreading and from scattering by the residual gas in the vacuum chamber.

Two damping factors appear once oscillations are excited. As the magnetic field increases, their amplitude is diminished in proportion to  $H^{-1/2}$ . At high energies further damping is introduced by radiation loss. For a radially symmetric field, no forcing factor is present to maintain the amplitude of oscillations following the initial exciting pulse.

#### D. Focusing

Although the equilibrium radius is fixed by the flux condition, it is necessary to provide magnetic vertical focusing to keep the beam in or near the median plane during the long total path length, which, in larger instruments, is greater than 10 km. This is readily accomplished with wedge shaped pole faces giving a magnetic field which is bowed outwardly over the region of the electron orbits as shown in figure 89 .

The amount of focusing that can be provided is limited by the accompanying radial decrease in magnetic field since the concurrent stability to radial oscillations is possible only when the restraining force of the mag-

netic field falls off with radius less rapidly than the centrififical force on the electron. The magnetic field, therefore, must decrease with radius at a rate less than  $1/r$ , and stable, focused orbits are obtainable when

$$H \sim \frac{1}{r^n}$$

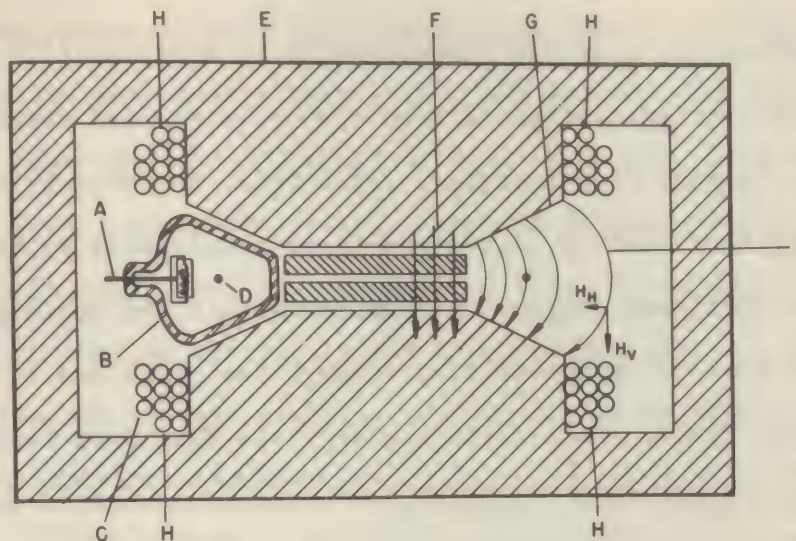
$$0 < n < 1$$

The defocusing effects of space charge and scattering are strongest at low electron velocities when, fortunately, magnetic focusing is most effective.

#### References

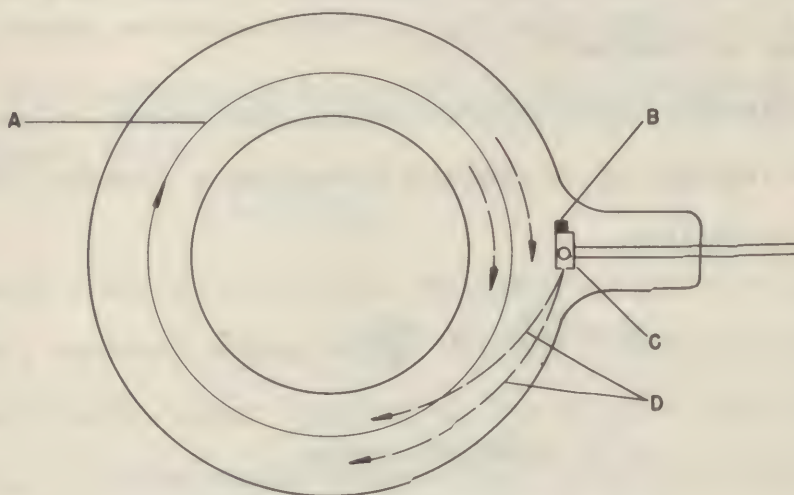
1. Kerst, D. W., Phys. Rev. 58, 841 (1940)
2. Kerst, D. W., Phys. Rev. 60, 47 (1941)
3. Kerst, D. W., Rev. Sci. Inst. 13, 387 (1942)
4. Kerst, D. W., and Serber, R., Phys. Rev. 60, 53 (1941)





BETATRON CONSTRUCTION

- |                                       |  |
|---------------------------------------|--|
| A. ELECTRON INJECTOR                  | F. FLUX PATH   |
| B. "DOUGHNUT" VACUUM CHAMBER          | G. POLE FACES, WEDGE SHAPE FOR FOCUSING  |
| C. AUXILIARY COIL FOR EXTRACTING BEAM | H. MAGNET ENERGIZING COILS   |
| D. EQUILIBRIUM ORBIT POSITION         | I. BOWED MAGNETIC FIELD IN REGION OF ORBIT SHOWING HORIZONTAL COMPONENT NECESSARY FOR FOCUSING |
| E. MAGNET YOKE                        |  |



ELECTRON PATHS IN BETATRON

- |   |
|---|
| A. EQUILIBRIUM ORBIT  |
| B. TUNGSTEN TARGET  |
| C. INJECTOR CONTAINING FILAMENT AND ELECTROSTATIC ACCELERATING SLIT |
| D. ELECTRONS LEAVING INJECTOR ON OSCILLATING ORBITS                 |

Fig. 89

## 16. SYNCHROTRON

### A. Description

The synchrotron, proposed independently by McMillan (1) and Veksler (2), employs certain properties of both the cyclotron and betatron to accelerate electrons to very high energies. Electrons, injected by an electron gun with a velocity near that of light, are first accelerated by betatron operation for which flux bars, figure 90, located within the orbit provide the necessary time rate of change of flux through the orbit due to the slowly increased magnetic field. At a certain energy, the flux bars become saturated, the flux remains essentially constant, and betatron operation ceases. At this time a constant radio frequency voltage is applied to the dees and the electrons then accelerated to high energies by cyclotron-like operation. Since electrons are injected with nearly the velocity of light, the radius increases by only a few percent during subsequent acceleration. The magnetic field, pole pieces, and vacuum chamber, therefore, are constructed as a narrow, annular ring as shown in figures 90, 91, 92.

The principle characteristic of the synchrotron is "phase-stability". The angular velocity of an electron traversing a circular trajectory normal to a magnetic field is

$$\omega = \frac{eH}{mc} = \frac{e\hbar}{E}$$

$e$  = electron charge.

$m$  = relativistic electron mass.

$H$  = magnetic field.

$c$  = velocity of light.

$E$  = total electron energy: Kinetic plus rest energy.



As the electron energy and its relativistic mass increases, the magnetic field at the orbit must increase correspondingly if the electron is to remain in or near resonance with the accelerating electric field. With a magnetic field which increases slowly during the period of acceleration, oscillations in phase are stable and tend to be dampened. In effect, the phase stability forces the particles to remain in or near resonance with the electric field with only small departures from exact resonance. This is seen from the fact that an electron traversing the dee gap too early, i.e., at a time when the dee voltage is low, receives a smaller energy impulse than an electron arriving late when the voltage has increased. The angular velocity of the first electron is therefore reduced and on successive transits will arrive later at the gap. The second electron, however, increases in angular velocity and arrives at the dee gap earlier on successive cycles. The electrons initially injected therefore tend to bunch about an equilibrium phase with respect to the electric field during the early stages of synchrotron operation. Oscillations continue about the equilibrium phase throughout acceleration but their amplitude is diminished by both radiative loss and by the increasing magnetic field;

$$A \sim H^{-1/2}(3)$$

If the magnetic field were constant, the electrons would not gain energy but would maintain a constant average energy while performing phase oscillations about the equilibrium phase. However, if the magnetic field is increased adiabatically, i.e., an infinitesimal increase in  $H$  during one cycle of the particles, the phase oscillations remain stable and electron bunch as a whole must receive a net increase in energy at each transit if the angular frequency is to remain constant while the field increases. The ultimate energy is not

limited by the radius as in the cyclotron since here it remains nearly constant, but rather, by radiative losses from the electrons at very high energies. An energy can, in principle, be reached for which the energy loss by radiation just equals the energy gained per turn.

In principle, the structure of the synchrotron magnet is similar to the core of a large transformer. The yoke is built up from laminated plates of iron to reduce excessive heating and loss from eddy currents. The annular pole pieces similarly are constructed of thin laminations bonded with a non-conducting material and shaped to give the requisite bowed field required for focusing. The varying magnetic field is produced by coils wound on the upper and lower pole pieces and energized by discharges from banks of condensers, periodically.

Structural details of a synchrotron built for the Atomic Energy Commission at the University of California are shown in figures 90, 91, 92.

## B. Motion of Particles

### 1. Synchronous Orbits:

The condition for a synchronous orbit are satisfied when the electron rotates in resonance with the electric field at an angular velocity given by

$$\omega_s = \frac{eH}{m_s C} = \frac{eH}{E_s}$$

which alternatively gives the equilibrium energy at a particular value of H. The angular position of an electron with respect to the gap when the dee voltage is zero is referred as the phase,  $\phi$ . In the synchronous orbit, the phase is constant and results in an energy gain per turn of  $eV \sin \phi$ , where V is the peak r.f. dee voltage. The equilibrium or synchronous phase can be determined from the conservation of energy (1,3)



$$eV \sin \varphi_s = \Delta E_s + L_s - 2\pi r_s V_1$$

$$\Delta E_0 = \frac{2\pi e_0}{w^2} \frac{dH}{dt} = \text{energy gain per turn.}$$

$L$  = radiation loss per turn.

$r = (E^2 - m^2 c^2)/300 H = \text{equilibrium radius.}$

$V_1$  = voltage due to changing magnetic flux. This contribution is usually small after synchrotron operation has started.

## 2. Phase Oscillations

Electrons which were not started in a synchronous orbit or otherwise arrive at the gap at a time differing from the equilibrium phase, are retarded or advanced on successive transits and thus continue to execute stable oscillations in phase as well as in radius and energy about the synchronous values. The equation of motion of the phase,  $\varphi$ , is given by the relations, (1,3,4),

$$\frac{d}{dt} \left( \frac{E_s}{w_s^2 K} \varphi \right) + \frac{r_s L'_s c^2 \varphi}{2\pi(1-n)Kv_s^2 w_s} + \frac{eV}{2\pi} \sin \varphi = \frac{eV}{2\pi} \sin \varphi_s$$

$$K = 1 + \frac{n}{1-n} \frac{c^2}{v_s^2} \sim \frac{1}{1-n}$$

$$n = - \frac{d \ln H}{d \ln r}$$

$$L'_s = \frac{dL_s}{dr}$$

$$v_s \sim c$$

For oscillations of small amplitude, the energy oscillates about the equilibrium value by the amount

$$\Delta E = - \left( \frac{eV E_s \cos \varphi_s}{2\pi K} \right)^{1/2} (\varphi_m - \varphi_s)$$

$\varphi_m$  = maximum phase amplitude.

The corresponding change in radius is given by

$$r = \frac{c^2}{v_s^2} \frac{r_s}{1-n} \frac{\Delta E}{E_s}$$

In general, the amplitudes  $\varphi_m - \varphi_s$ ,  $\Delta E$  and  $\Delta r$  vary as

$$\varphi_m - \varphi_s \sim ([1-n]vE)^{-1/4}$$

$$\Delta E \sim E_s ([1-n] \frac{v}{E_s})^{1/4}$$

$$\Delta r \sim r_s (v/[1-n]^3 E_s^3)^{-1/4}$$

The frequency of phase oscillation is small compared to the orbital frequency of the electrons. From the equation for the phase, the frequency is found to be (3)

$$\Omega = w_s \left( \frac{eVK \cos \varphi_s}{2\pi E_s} \right)^{1/2} \left( 1 - \frac{1}{16} [\varphi_m - \varphi]^2 \right)$$

These oscillations were shown to be stable for adiabatic changes in the magnetic field (3).

### 3. Orbital oscillations

Both vertical and radial oscillations in the orbits may occur with frequencies comparable to the rotational frequency of the electron. Calculations of these frequencies (5) gave values of

$$\Omega_{(vert)} = n^{1/2} w$$

$$\Omega_{(rad)} = (1-n)^{1/2} w$$

$$n = \frac{d \ln H}{d \ln r}$$

which are damped in part by increasing magnetic field and in part by radiation loss at high energies.



### C. Energy Loss by Radiation

Electrons moving in circular orbits with velocities very close to the velocity of light lose energy by radiation arising from radial acceleration. The incoherent radiation energy loss per turn is given by

$$L = \frac{4\pi e^2}{3r} \left( \frac{E}{mc^2} \right)^4$$

Further accelerations resulting from orbital and phase accelerations lead to radiative energy loss which dampen such oscillation. For phase oscillation, the decrease in phase amplitude per turn due to radiation damping is

$$\Delta(\varphi_m - \varphi_s) = \frac{1}{2} (3-4n) \frac{L_s}{E_s}$$

### D. Synchrotron Operation

Electrons are injected with an energy of approximately 60 kev into the annular magnetic field near the beginning of the magnetic cycle. By betatron action above (r.f. field off), they are then accelerated by a constant torque to an energy of the order of 2 mev and a velocity of approximately 0.99 c. By this means, the orbits are rapidly brought clear of the injector and to a radius which changes very little on subsequent acceleration. The transition from betatron to synchrotron operation takes place when  $E_\beta = E_s$  or  $r_\beta = r_s$ . During the period of transition the electrons increase in angular velocity until their period matches the r.f. field which is slowly increasing in amplitude to its peak value. Those electrons lying within the proper phase angles are then "locked" into synchronism and gradually bunched. Betatron action effectively ceases with saturation of the flux bars, and the electrons then rapidly derive energy from the r.f. field.

Despite the bunching effect, an energy spread persists because of the finite duration of the injection time. Assuming the injection interval to correspond to the time required for an electron to increase from radius  $r_0$  to  $r_\beta$ , the energy spread can be calculated from the expression, (3),

$$\delta E = (1 - n) (2mc^2 T) \frac{r_0 - r_\beta}{r_\beta}$$

$T$  = kinetic energy of electrons at injection.

$r_0$  = injector radius.

$r_\beta$  = betatron equilibrium radius.

#### References

1. McMillan, E. M., Phys. Rev. 68, 143 (1945)
2. Veksler, V., J. Phys. USSR 9, 153 (1945)
3. Bohm, D., and Foldy, L., Phys. Rev. 70, 249 (1946)
4. Frank, N. H., Phys. Rev. 70, 177 (1946)
5. Kerst, D. W., and Serber, R., Phys. Rev. 60, 53 (1941)



# SYNCHROTRON -

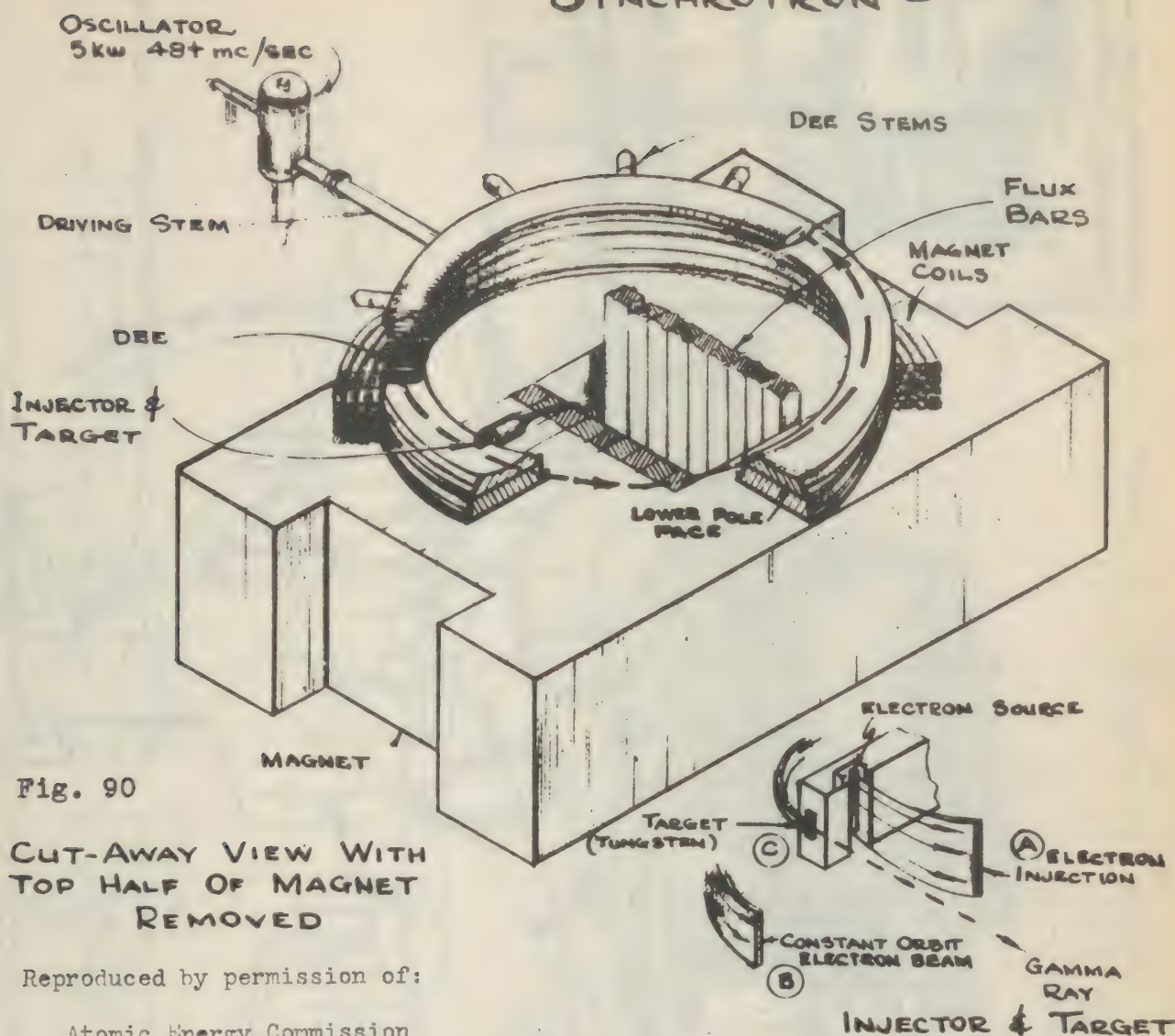


Fig. 90

CUT-AWAY VIEW WITH  
TOP HALF OF MAGNET  
REMOVED

Reproduced by permission of:

Atomic Energy Commission

Electrons are injected (ref. A) into the circular vacuum chamber by a hot-cathode electron gun at approximately 60 KV. Operating first as a betatron, the electrons are accelerated by means of an electromotive force induced by changing the magnetic field. The field is varied by discharging, 6 times per second, a capacitor bank through the magnetic windings.

Because of relatively small mass of electron (approx.  $\frac{1}{2000}$  mass of proton), its velocity is almost a constant (approaching the velocity of light) at high energies, and owing to the relativistic effect, its mass increases greatly. At 2 Mev, electrons move at 98.89% velocity of light and have increased in mass 5 times; at 300 Mev, 99.994% velocity of light and 600 times increase in mass.

After reaching 2 Mev, the electrons are further accelerated by an oscillating electrostatic field applied to the dee shown above, similar to cyclotron operation. Moving at constant velocity and accelerated by a fixed frequency, electrons revolve in a constant orbit ( ). Employing the principle of "phase stability", relativistic mass increase at high velocities is compensated for by varying the magnetic field strength over a large range, and not by varying the frequency as is done in the synchro-cyclotron. Upon reaching maximum energy, electrons are caused to spiral inward to strike the tungsten target ( ) producing 300 Mev gamma rays.

# THE SYNCHROTRON

CUT AWAY TO SHOW INTERIOR

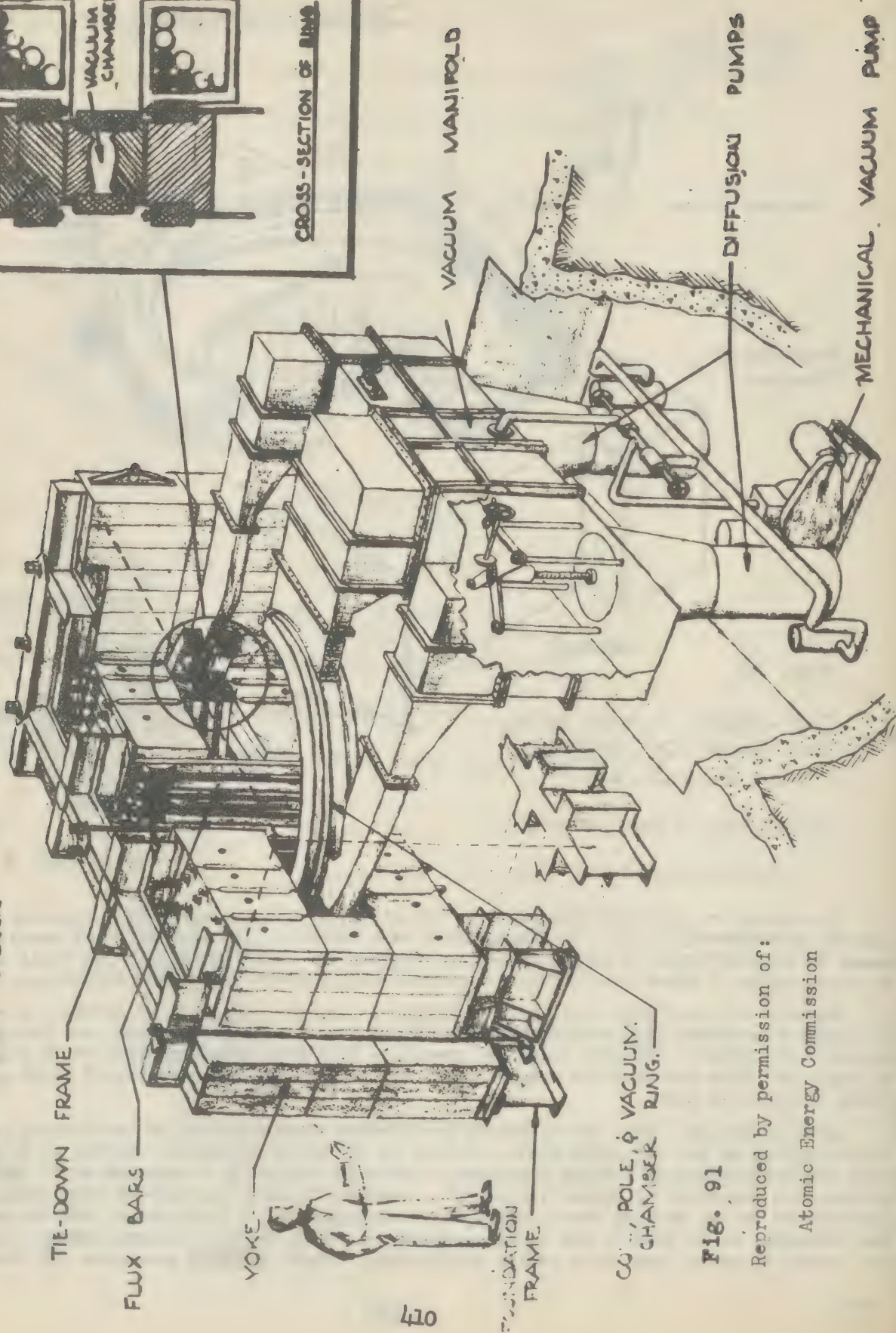


Fig. 91

Reproduced by permission of:

Atomic Energy Commission



# SYNCHROTRON VACUUM CHAMBER ASSEMBLY

EACH POLE PIECE COMPOSED OF FORTY SECTORS. EACH SECTOR LAMINATED OF .014 INCH THICK SPECIAL STEEL SHEET CEMENTED WITH INSULATING  $\frac{1}{4}$ " VACUUM-PROOF "REDUX". INDIVIDUAL SECTORS ARE SEPARATED WITH  $\frac{3}{32}$  INCH RUBBER GASKETS.

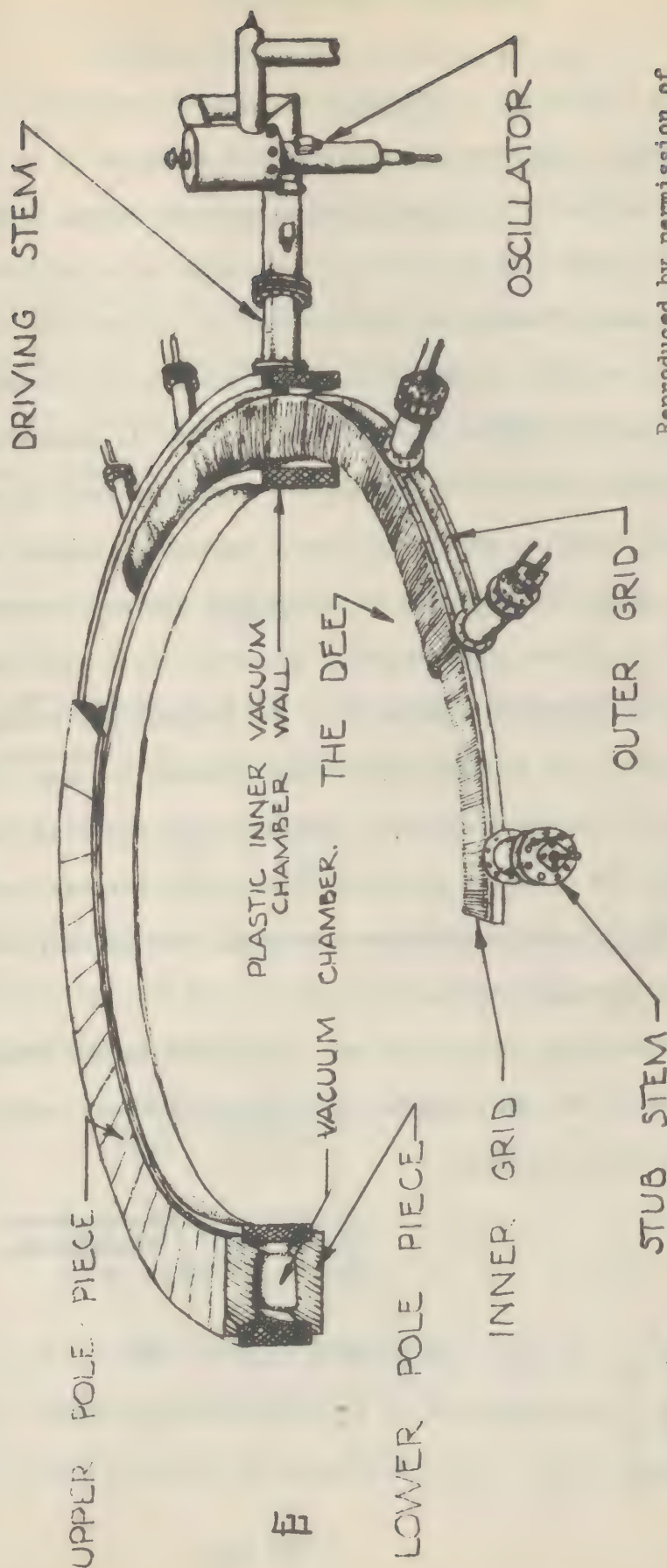


Fig. 92

Reproduced by permission of  
Atomic Energy Commission

OUTER GRID BOLTED TO OUTER VAC. CHAMBER WALL IN ASSEMBLY. DRIVING & STUB STEMS BOLTED TO OUTSIDE OF WALL AND CONNECTED THRU WALL TO INNER GRID OF DEE.

## 17. CYCLOTRON

### A. Description

The cyclotron, or magnetic resonance accelerator, first proposed and developed by Lawrence, (1) enables high energies to be imparted to heavy charged particles by repeated accelerations across a comparatively small electric field. Ions formed at the center of a uniform magnetic field of 10,000 gauss or more, are accelerated in the gap between two hollow, D-shaped electrodes, known as dees, to which a high frequency voltage of 10-100 KV, peak, is applied in opposite polarity as shown in figure 93. An ion starting from the center of the magnetic field is constrained to move in nearly circular orbits of slowly increasing radius as it is accelerated by successive impulses in traversing the gap between the dees. Synchronization of the high frequency electric field with the frequency of rotation of the particle ensures that the maximum dee voltage occurs at, or somewhat before, the instant the particle passes the gap. During the remainder of its path in the field-free region within the dees, the particle is unaffected by the charging electric field which has reversed its polarity when the particle again enters the next gap. Two pulses, therefore, are given a particle in each cycle.

The magnetic field does not contribute to the energy and serves only to constrain the particle to circular paths whose radius at any instant depends on the velocity:

$$r = \frac{mv}{eH} \approx \frac{1}{H} \sqrt{\frac{2mV \sin \phi}{e}}$$

$m$  = mass of particle.

$v$  = linear velocity.



$e$  = charge of particle.

$H$  = magnetic field strength.

$n$  = number of traversals of gap.

$V$  = peak r.f. voltage.

$\phi$  = phase of particle: angular position from gap when  $V = 0$ .

The angular velocity of the accelerated particle, is independent of the energy and the linear velocity provided the relativistic increase in mass is negligible, i.e., for velocities corresponding to alpha particle velocities of 50 mev or less. The period of rotation is then constant with magnitude given by

$$T = \frac{2 \pi mc}{eH}$$

The frequency of the particle, as well as of the oscillating electric field, are correspondingly constant with a magnitude given by

$$\omega = \frac{1}{T} = \frac{eH}{2 \pi mc}$$

The highest energy to which a particle can be accelerated is determined, aside from the limitation imposed by the relativistic increase in mass, by the magnetic field strength and radius:

$$E_{\max} = \frac{e^2 R^2 H^2}{2m c^2}$$

$R$  = maximum radius.

$c$  = velocity of light.

If the frequency and peak voltage is kept constant and only the magnetic field altered for the acceleration of particles of different mass, the maximum energy to which the particles can be accelerated, for a given radius is

directly proportional to the mass:

$$E_{\max} = 2 \pi^2 m \omega^2 R^2$$

The most efficient utilization of the beam is made by inserting a probe of the substance to be bombarded into the beam at the maximum radius. This method, however, proves to be inconvenient for routine bombardments and unsatisfactory in experiments where a directed or collimated beam is essential. Beam extraction is accomplished, for energies up to 50 mev at least, and possibly higher, by electrostatic deflection of the beam after it has attained maximum energy. A long curved plate located a quarter or third of the distance along the periphery of the orbit is operated at a sufficiently high negative potential to deflect the beam out of its normal orbit and into the region where the magnetic field begins to fall off rapidly. In this way the beam can be directed into a tangentially located target chamber and if necessary brought out of the vacuum tank through a foil window.

Alternative schemes have been proposed which may prove more successful for the extraction of very high energy beams ( > 100 mev) for which simple electrostatic deflection may be impracticable. For example, if the magnetic field is weakened locally by shims along a spiral path leading outward from the maximum radius, ions of the proper energy entering this region can be lead out to the periphery of the field where it falls off rapidly and the ions will then follow nearly a straight path (2). Magnetic deflection of this kind combined with appropriate electric fields may ultimately provide the most satisfactory deflector system in such cases; however, investigation of such schemes is still in progress at the present time.

The general structural features are illustrated by the diagram of the 184 inch cyclotron at the Radiation Laboratory of the University of California shown in figures 94 , and 95 .



## B. Ion Paths

The ultimate fate of an ion depends largely on how it gets started. Less than  $10^{-4}$  of the ions produced at the source ever reach the target. The greater proportion is lost immediately through neutralization by collision with parts of the source and the dees, and partly by recombination. Furthermore, ions can be started on stable orbits only during a part of electric field cycle. Those which start long before the dee voltage has reached a maximum value are ultimately defocused and strike the dees. Ions starting long after the dee voltage has passed a maximum value may be accelerated and find stable orbits, but these still have little probability of reaching the target. These ions receive only a fraction (approximately  $1/2$  or less) of the accelerating voltage at each transit past a gap and must perform correspondingly more cycles and, hence, traverse a greater path length, to reach the maximum radius and energy. The probability of collision with the residual gas in the tank becomes greater and, in general, such ions are either deflected by collisions to the dee walls or are knocked out of resonance with electric field. The ions which successfully reach the target, therefore, are those which start within a time interval corresponding to the portion of the electric field cycle near and somewhat past the maximum as shown in figure 93 .

Three features of cyclotron orbits are important to its operation: 1, stability to small oscillations superimposed on the normal spiral path; 2, the tendency of ions to remain in or near the median plane between the pole pieces; 3, the stability of resonance between the ion rotational frequency and the oscillating electric field. The necessity for a high order of stability is apparent from the fact that in large cyclotrons, the ions will have traveled a total length of hundreds of meters before arriving at the target where the beam should have a cross sectional area of only a few

square cm. Certain properties of the orbits must therefore correct even small deviation of the ion in transit if it is to remain within the small solid angle necessary to reach the target. The stability of ion paths for those ions which start during the favorable part of the cycle depends upon the focusing properties inherent in the design of the cyclotron.

Electrostatic focusing is important during the first part of the acceleration before the ions have reached large radii and high energies. When an ion, which is not in or parallel to the median plane, traverses the first half of the gap between dees, the electric field distribution focuses the ion toward the median plane as shown in figure 96. In the second half of the gap, symmetry of the field leads to a defocusing effect but the ion momentum has increased simultaneously and the angle of deflection is less. The net effect therefore, is focusing. If the ion traverses the gap shortly after peak voltage has been reached, the focusing effect is further augmented since the field weakens during transit and the particle is focused both by its momentum increase and also by the asymmetrical field it experiences. The reverse process follows when transit occurs during the part of the cycle when the voltage is increasing rapidly; defocusing is enhanced and may exceed all focusing effects. The ion is then lost to the dee or other structural parts after a sufficient number of periods.

Magnetic focusing fortunately becomes predominant at large radii and high energies where electrostatic focusing becomes ineffective. This effect arises from the bowed magnetic field near the edge of the gap; providing horizontal components in the magnetic field as shown in figure 96. Ions which have wandered out of the median plane are continuously forced back by interaction of their vertical velocity components with the horizontal field component in the same way that the particle is constrained to



move in a circular or spiral orbit by the vertical field.

Both the electrostatic and magnetic focusing effects provide the requisite restoring force to ensure the stability of oscillations of the orbits about the median plane and the normal orbit. When the magnetic field possesses perfect radial symmetry, free oscillation can occur with both vertical and radial components and only with periods equal to or longer than the rotational period of the particle. Free oscillations in cyclotrons are neither damped nor forced once they are excited.

Oscillations in phase, i.e., the angular position of the particle with respect to the gap when the dee voltage is zero, are stable for certain orbits. A particle arriving at the gap early or late is retarded or advanced accordingly on successive transits and continues to execute simple harmonic motion about the equilibrium phase. Phase oscillations introduce a characteristic precessional motion in the normal orbit causing the center of rotation to move in a circle with the same period as the phase oscillation.

Asimuthal asymmetries in the magnetic field lead to forced oscillations with frequencies equal to, or greater, than that of the rotational frequency. Small oscillations of this form are usually stable and sometimes must be tolerated.

### C. Ion Source

The ion source in a cyclotron is accurately located at the center of the magnetic field and directly above or below the gap between the dees, corresponding to the position in the median plane from which the greatest number of ions can be started on stable orbits. In its conventional form, the ion source consists of a heavy helical tungsten filament mounted in a closed copper structure with a capillary outlet directed toward the median

plane and parallel to the magnetic field as shown in figure 93. The entire structure is supported from the tank wall by an appropriate mechanism to allow exact adjustment of its position with respect to the dees for optimum beam output.

The gas to be ionized, hydrogen, deuterium, or helium, is piped into the space around the filament from where it leaks out through the capillary in which it is ionized by electron bombardment. An ion cloud is then formed in the central region between the dees from where ions are pulled, each half cycle, into alternate dees by the strong electric field. A tungsten capped block mounted on the side of the tank opposite the source frequently serves as a cathode; operating at several hundred volts positive with respect to the filament structure. Filaments have been successfully operated on direct current, and on low and high frequency current.

Details of the design of ion sources vary somewhat depending upon the particles to be accelerated and the particular cyclotron in which it is used. Usually the same source can be employed for protons and deuterons. Alpha particle sources, however, are made more massive to withstand the higher rate of deterioration from positive ion sputtering. Water cooling on the filament leads is essential as well as good thermal contact between parts of the source to prevent local melting from ion bombardment.

#### D. Cyclotron Targets

##### 1. Design features of Targets

A variety of target forms and techniques are employed, depending largely upon the physical properties of the bombarded material, the purpose of the bombardment, and whether it is bombarded in the vacuum chamber of the cyclotron or in an external chamber into which the beam is deflected.



An internal target requires special consideration in its design and is limited to the comparatively few substances which are stable in a vacuum at elevated temperatures. Although a slightly higher bombardment efficiency can be obtained than for an external targets, the limitations and operational difficulties make internal targets inconvenient for routine bombardments. Nevertheless, internal targets are frequently used in one of the two possible forms. In the first, the target material is mounted at the end of a probe and inserted directly into the circular orbit of the beam at its maximum radius, through a vacuum seal in the tank wall (3). In the second form, the target is mounted in a chamber located beyond the deflector. Probe targets are usually less satisfactory for most purposes because of engineering and operational difficulties but it possesses the advantage that considerably greater beam currents can be had and the deflected beam to the target chamber can still be used simultaneously although with some loss of intensity.

Bombardment in a target chamber, into which the beam is deflected, is the most widely practiced use of internal targets (4). Such targets can be changed rapidly by means of a vacuum lock and, in general, engineering and operational factors are more favorable.

External targets are also bombarded in a target chamber located beyond the beam deflector but are separated from the vacuum tank by a thin aluminum window through which the beam emerges. Comparatively little difficulty is experienced with these targets since occluded gases, high vapor pressure and decomposition in no way affects operation of the cyclotron. Such targets can be operated, when necessary, in an atmosphere of helium at a reduced pressure, to prevent oxidation and to avoid excessive beam absorption. In addition to simplicity of operation and design, gases and liquids can be bombarded as well as most solid substances.

Practically all substances must be mounted on a water cooled copper target plate to be bombarded, both for internal and external targets. The details of the design of a target and the choice of target material, is, in general, governed by heat transfer, bonding properties, stability, bombarding efficiency, and the subsequent chemistry. The relative importance of the first three factors in the design difference of internal and external targets is chiefly one of degree, whereas, the last two factors apply equally well to both targets.

## 2. Heat Transfer.

Rapid transfer of heat must be provided for between the target substance and the cooling system. Although as little as 25 watts may be delivered by the beam, the equivalent heat is liberated usually in a very small volume of the target material. The bonding to the water cooled copper target plate should, therefore, ensure good thermal contact and the thickness of the material limited to prevent high surface temperatures and local overheating due to steep thermal gradients. This is particularly important for internal targets when the material has an appreciable vapor pressure or a tendency to decompose at elevated temperatures.

The temperature rise of the water in the cooling system provides a convenient means of estimating the bombarding beam current from the relation, (3),

$$i = 4.18 \frac{Q \Delta t}{E}$$

$Q$  = flow rate.

$\Delta t$  = temperature difference between inlet  
and outlet water.

$E$  = energy in mev.



### 3. Target Materials and Bonding.

The most satisfactory processes for bonding materials to the copper target plate are electroplating, soldering, and brazing. They are applicable, however, only to those few metallic elements and alloys (including beryllium which can be silver soldered) that are stable under bombardment and at elevated temperature, particularly when used with internal targets. Materials that cannot be bonded by these processes are usually prepared in the form of suitable compounds or mixtures. Many of these can be fused and will adhere to a copper target plate on which "V" shaped grooves have been milled in a direction parallel to the plane of the beam and to a depth corresponding roughly to the range of the particles in the target material. A thin layer of the material is spread over the grooves and the plate heated from below with a torch or in a furnace until the material fuses into the grooves. Better heat transfer to the plate during bombardment is obtained if the grooves are not quite filled.

The choice of compound or mixture used for this type of target is determined mainly by its binding strength and stability. For internal targets this is particularly important; it should not decompose or melt or have a vapor pressure high enough at elevated temperatures to interfere with operation of the cyclotron or to cause loss of material. These factors are less stringent in external targets but it is still desirable to use materials with high resistance to thermal shock and very low vapor pressure to reduce loss of active material.

The suitability of a substance for internal targets is difficult to predict beforehand but several generalizations of the properties of compounds best suited for target materials have been proposed by Reid (4) and Weil (5).

- A. Ionic compounds of two elements probably will not adhere well.
- B. Ionic compounds in which an ion is diatomic adhere better. If the anion is the metaform, bonding may be good.
- C. Compounds which polymerize may be satisfactory.
- D. Compounds which form a glassy-non-crystalline solid generally form a good bond.

A list of compounds used for internal targets is given in table

Many materials which are stable under target conditions but cannot be fused easily to the target, can be bombarded in the form of powder. Targets in this form are prepared by filling a shallow recess in a water cooled copper block with the powder and sealing it in with a cover of thin tantalum foil (6). It is then bombarded externally, usually in an atmosphere of helium at reduced pressure. Helium is preferable to other inert gases since it does not appreciably absorb the beam.

Both gaseous and liquid substances can be readily bombarded externally in appropriately designed containers. One end is sealed with an aluminum or tantalum foil through which the beam enters. As in solid targets, proper consideration should be given to the dissipation of heat produced in the target volume.

#### 4. Target efficiency.

From the point of view of beam utilization, target efficiency is judged by the proportion of the beam producing the desired reaction. An efficiency of 100% is assured, therefore, only in a target consisting wholly of the isotope producing the reaction. The presence of isotopes of the same species reduces the efficiency by the amount of their total abundance compared to the isotope producing the reaction. When the target material is a compound, or



mixture, the efficiency is still further reduced but in a more complicated manner since the stopping power of the constituent atoms is different. Obviously, compounds containing only a small percentage of the reaction element should be avoided when efficient bombardment is sought after. The volume of target material is also a factor in the efficiency if its depth is less than the useful range of the particles and its surface does not completely cover the beams cross section.

So far as bombardment efficiency is concerned, it would appear desirable to make the target more than necessarily massive to insure complete beam absorption in the target material, however, other considerations make it desirable to reduce the volume of material to the minimum required for complete beam utilization. This is necessary to obtain the highest specific activity and to reduce the volume of material handled in chemical isolation of the active isotope. The surface area should correspond to the beam cross section which is usually known and reasonably stable. The depth, on the other hand, should equal the maximum useful range of the particles in the particular target material. The useful range need not correspond to the total range of the particle in the substance. When a threshold energy for the reaction exists, that portion of the residual range in which the particle energy is less than the threshold does not contribute to the reaction and might just as well lie within the copper target plate. In estimating the target thickness, therefore, a length equal to the threshold range should be subtracted from the total range in the material. Any scattering effects in targets, particularly of heavy elements and for low energies would increase the effective thickness of the target.

The ranges for protons, deuterons, and alphas particles are given for a variety of substances in the section on alpha particles. In elements

for which ranges are not given, a rough approximation of the range, good enough for this purpose, can be obtained by extrapolating from the range-energy data for an element of nearly the same atomic number given in the graphs. If  $R_0$  is the known range of a particle at a particular energy in an element of atomic number  $Z_0$ , the range,  $R$ , in another element with atomic number  $Z$  is

$$R = R_0 \frac{Z_0 N_0}{Z N}$$

$N_0$  = number of atoms per cc of atomic number  $Z_0$ .

$N$  = number of atoms per cc of atomic number  $Z$ .

When the target material is a compound or mixture, it is possible in many cases to use an average atomic weight for computing the range by extrapolation, then

$$R = \frac{R_0 Z_0 N_0}{N \sum_{i=1}^n f_i Z_i}$$

$f_i$  = fraction of atoms with atomic weight  $Z_i$  in substance containing  $n$  atomic species.

Table 15. FUSABLE COMPOUNDS USED FOR CYCLOTRON TARGETS (4, 6)

element bombarded	target compound	element bombarded	target compound
B	B <sub>2</sub> O <sub>3</sub>	K	K <sub>2</sub> B <sub>2</sub> O <sub>4</sub>
O	Li <sub>2</sub> B <sub>2</sub> O <sub>4</sub>		K Cl
	B <sub>2</sub> O <sub>3</sub>	V	K V O <sub>3</sub>
F	Li <sub>3</sub> Al F <sub>6</sub>	Ge	Ge Cu <sub>2</sub>
Na	Na <sub>2</sub> B <sub>2</sub> O <sub>4</sub>	As	K As O <sub>2</sub>
P	Fe <sub>2</sub> P	Te	Tl Te O <sub>3</sub>
	Ca (PO <sub>3</sub> ) <sub>2</sub>		



### E. Synchro - Cyclotron

Early in the development of the cyclotron it was pointed out that the relativistic increase in mass of an accelerated particle would place a limit on the maximum energy derivable from the conventional form of cyclotron (9). With only a few percent increase in mass this effect becomes troublesome. The rotational frequency of the particle decreases and it arrives at the gap continuously later each cycle, i.e., the phase of the particle with respect to the fixed frequency electric field decreases until ultimately the particle crosses the gap at zero voltage and is no longer accelerated.

This limitation, inherent in a combination of fixed magnetic and fixed frequency electric field can be removed either by slowly increasing the magnetic field or by slowly reducing the electric field frequency during the period of acceleration (10, 11, 12, 13). The first method is impracticable in the magnetic structure required for the cyclotron. The second alternative however, has proved successful and has been used for the acceleration of deuterons to ~ 200 mev (14,15), corresponding to a mass increase of 10 percent. The frequency is slowly decreased over the period of time required by an ion, starting from the center, to reach the maximum radius. The percentage frequency modulation required depends on the mass of the ion and the maximum energy to which it is accelerated. Exact correspondence between the changing rotational frequency and the modulation frequency, or more correctly, their instantaneous rates of change, is not necessary since it has been shown that a slight mismatch in the two frequencies leads to phase oscillations about the equilibrium which are stable for an adiabatically changing field frequency. Precise control of the field, therefore, is not an important factor to contend with and the field frequency need only approximate the instantaneous rotational frequency of the particle.

Unlike the conventional cyclotron, the beam in this modified form must be pulsed. Ions are injected during an interval of a few microseconds only at the beginning of the modulation cycle at a time when the electric field frequency is in resonance with the particle frequency at low energies.

Aside from frequency modulation and a pulsed beam, the characteristics and structures of the synchro-cyclotron are similar to the conventional cyclotron. The ultimate energy which can be reached is now dependent wholly on practical considerations.

Modulation of the field frequency can be accomplished either electrically or mechanically and in the latter method, by varying either the inductance or capacitance of the resonant dee circuit. Modulation by electrical systems is still in the developmental stage (Columbia group) and no published literature is yet available. Several mechanical systems have been successfully developed providing frequency modulation up to 30% (14,15,16). In all cases variable capacitors were used.

For example: modulation of the 184 inch cyclotron at the University of California is accomplished with a rotating condenser mounted at the end of the dee stem (15,16) (figures 94,95). A set of stationary stator blades is mounted on the periphery of a motor driven insulated disc. A fixed coupling condenser plate mounted close to the disc completes the circuit. The entire unit is operated in a separate vacuum chamber to reduce sparking in the small gaps when the blades are adjacent. The maximum capacitance of the variable condenser in this scheme, where it is mounted at the end of the dee stem, is given by (16)

$$C = \frac{1}{Z\omega \tan\left(\frac{\omega l}{c} - \tan^{-1} \frac{1}{Z\omega C_d}\right)}$$



$L =$  Characteristic impedance of dee stem in ohms.

$\omega =$  Field frequency in radians per second  $= 2 f \pi$

$l =$  Total length of transmission line in cm.

$C_d =$  Capacitance of dee and stem in  $\mu\text{f}$ .

The transmission line length is  $l = \frac{2c}{\omega} \tan^{-1} \frac{1}{Z\omega C_d}$

$c =$  Velocity of light.

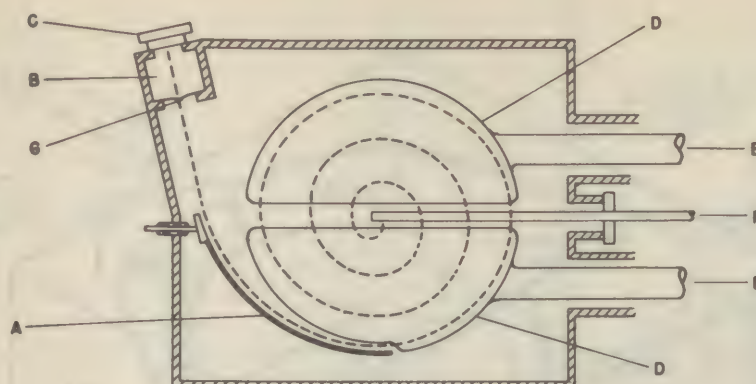
If  $C = C_d$ , the voltage across the condenser equals the dee voltage and the voltage node lies equidistant between the dee and rotating condenser.

#### References

1. Lawrence, E. O., and Livingston, M. S., Phys. Rev. 40, 19 (1932)
2. Skaggs, Almy, Kerst, and Lanze, Phys. Rev. 70, 95 (1946)
3. Wilson, R. R., and Kamen, M., Phys. Rev. 54, 1031 (1938)
4. Reid, A. F., Rev. Sci. Inst. 18, 501 (1947)
5. Weil, A. S., Reid, A. F., and Dunning, J. R., Rev. Sci. Inst., 18, 556 (1947).
6. Crocker Laboratory, University of California
7. Hull and Williams, Rev. Sci. Inst. 11, 299 (1940)
8. Irvine, J., Phys. Chem. 46, 910 (1942)
9. Rose, M. E., Phys. Rev. 53, 392 (1937)
10. McMillan, E., Phys. Rev. 68, 143 (1945)
11. Veksler, V. J., Phys. U.S.S.R., 9, 153 (1945)
12. Schiff, L. L., Rev. Sci. Inst. 17, 6 (1946)
13. Bahm, D., and Faldy, L., Phys. Rev. 70, 249 (1946)

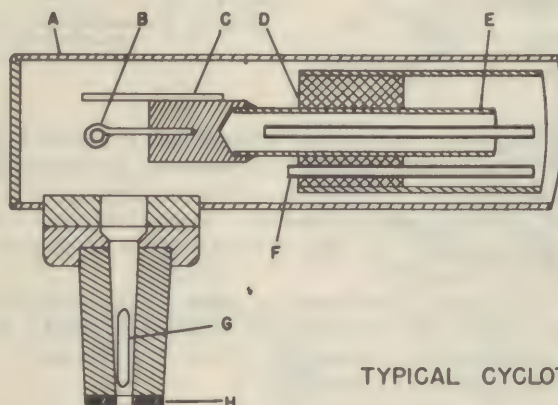
14. Richardson, J. R., et al., Phys. Rev. 69, 669 (1946)
15. Brobeck, W. M., et al., Phys. Rev. 71, 449 (1947)
16. Schmidt, F. H., Rev. Sci. Inst. 17, 301 (1946)





SCHEMATIC DIAGRAM OF CYCLOTRON

- A. DEFLECTOR
- B. VACUUM LOCK USED WITHOUT FOIL WINDOW FOR INTERNAL TARGET
- C. TARGET
- D. DEES
- E. DEE STEMS
- F. FILAMENT ASSEMBLY
- G. ALUMINUM FOIL USED AS VACUUM SEAL WITH EXTERNAL TARGET



- A. SUPPORT TUBE
- B. HELICAL TUNGSTEN FILAMENT
- C. MOLYBDENUM OR STAINLESS STEEL FILAMENT SHIELD
- D. FILAMENT LEAD INSULATOR
- E. FILAMENT LEADS AND CLAMP. SQUIRT TUBE SHOWN FOR WATER CIRCULATION
- F. GAS INLET TUBE
- G. VERTICAL SLOT IN CONE FACING DEE
- H. TUNGSTEN CAP

TYPICAL CYCLOTRON ION SOURCE

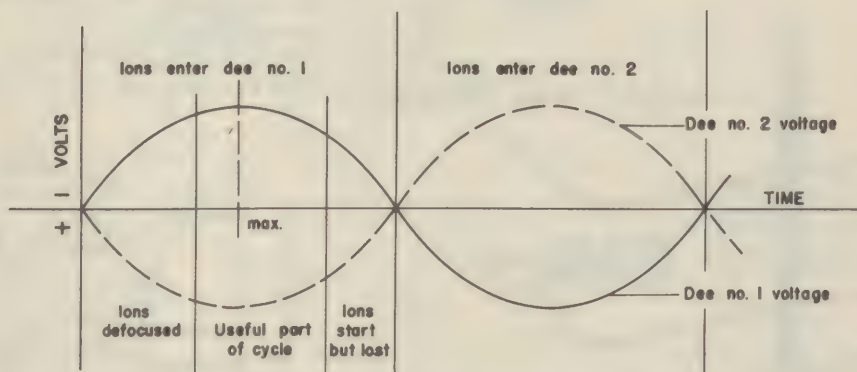
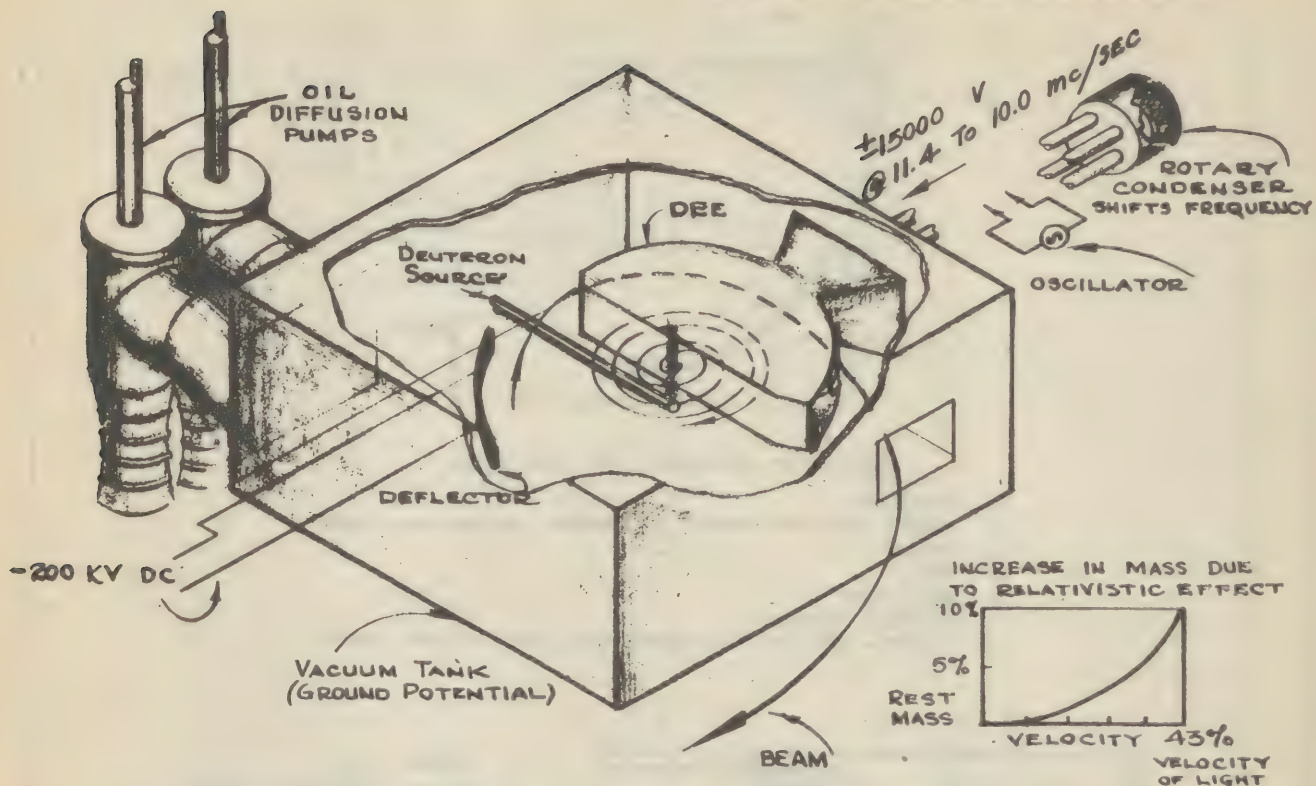


Fig. 93

STARTING PHASE OF PARTICLES IN THE CYCLOTRON

# 184" CYCLOTRON -



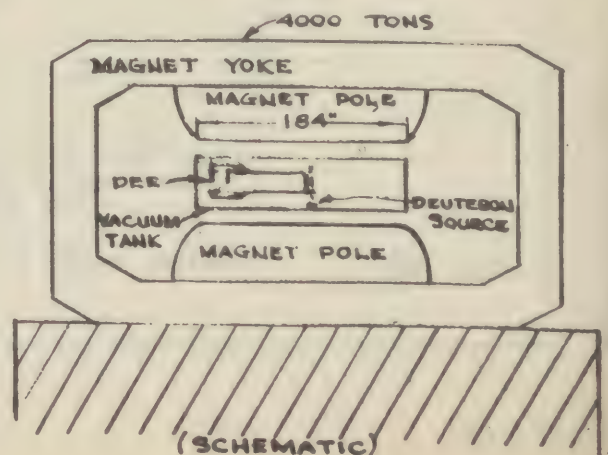
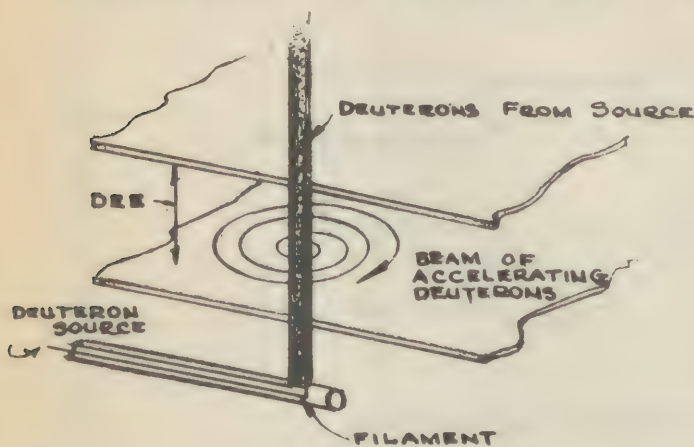
Inside the vacuum tank are positively charged nuclear particles (deuterons), entering at the center and revolving in a uniform magnetic field; as the energy increases, in step with the oscillating voltage on the "dee", these particles spiral outward. The energy gain is 20,000 electron volts per revolution; thus, it takes 10,000 revolutions to reach 200 Mev. At this energy particles are moving at 80,000 miles per second, or 43% the velocity of light.

The deuterons, as they approach the velocity of light, increase in mass (relativistic effect). To prevent the particles from lagging, and so failing to be accelerated, the oscillating frequency of the dee voltage is continuously changed. Thus the terms "frequency-modulated" (or FM) cyclotron, or "synchro-cyclotron".

Reproduced by permission of:

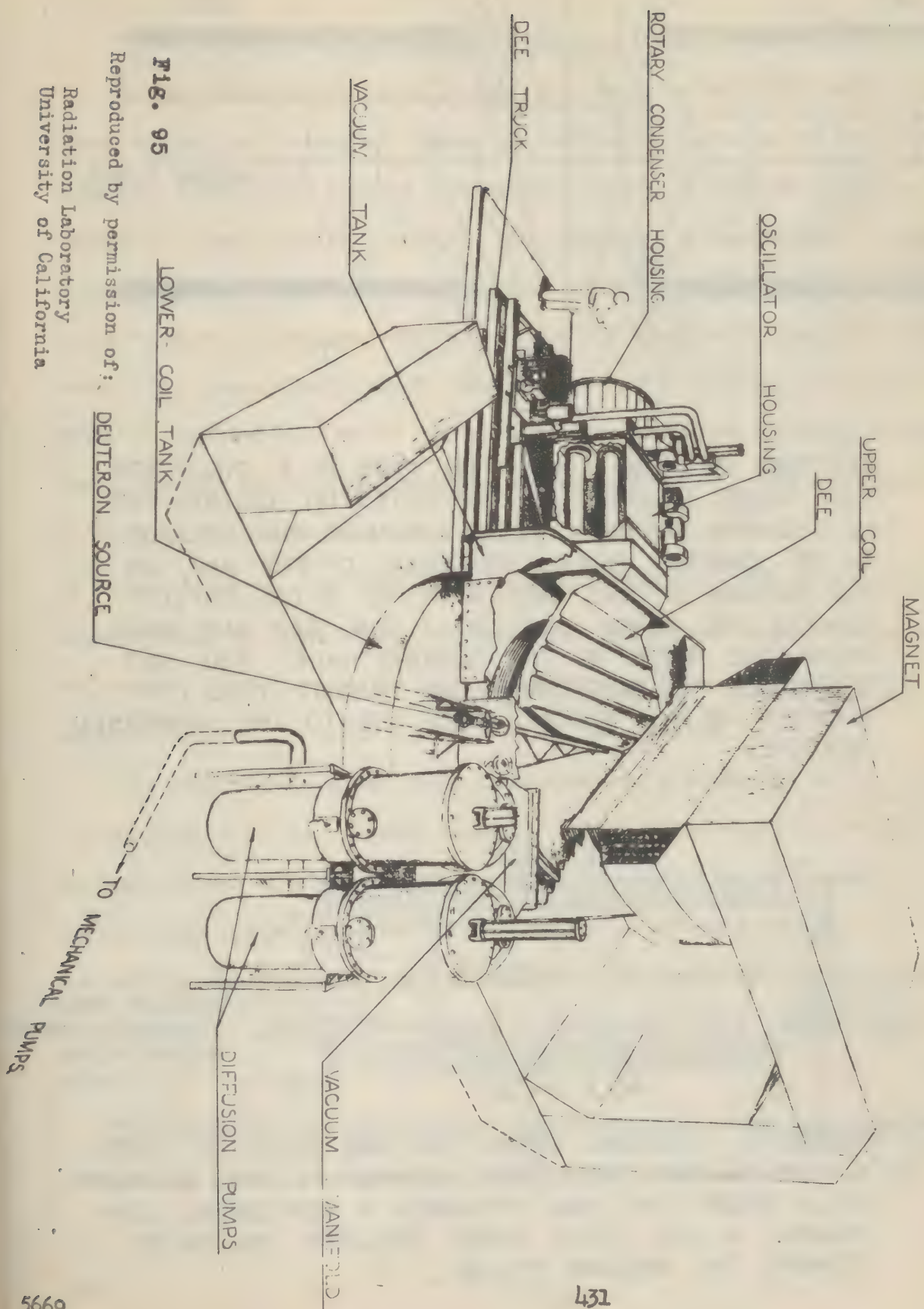
Radiation Laboratory  
University of California

. Fig. 94





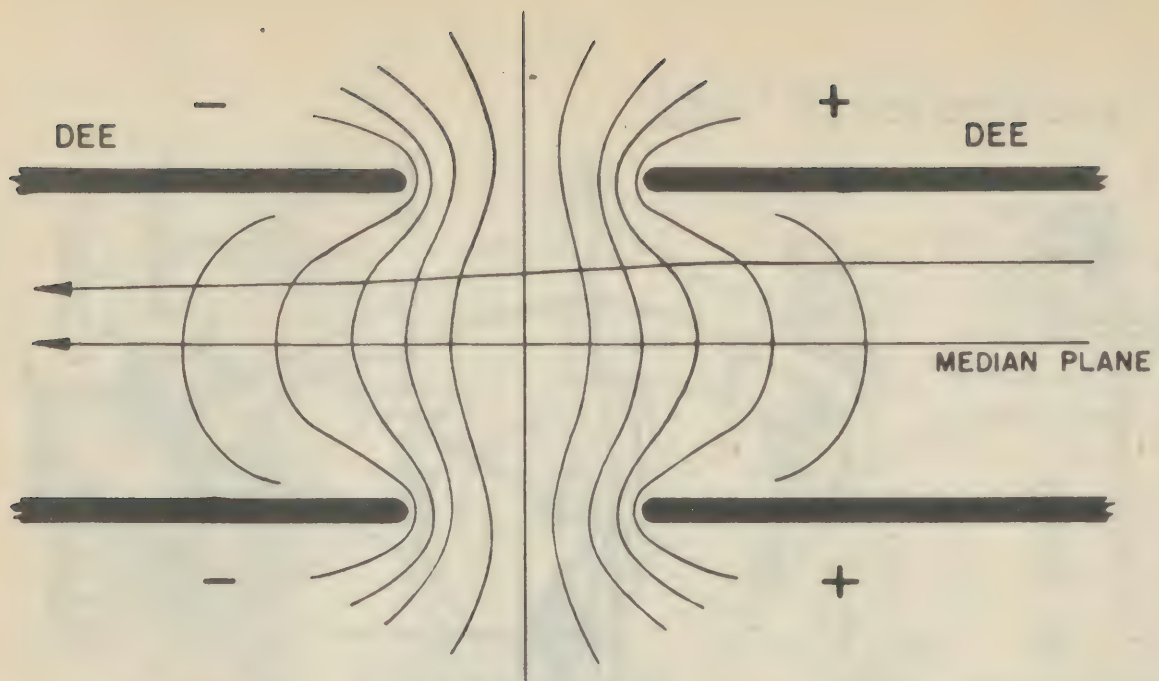
# THE 184" CYCLOTRON CUT AWAY TO SHOW INTERIOR



**Fig. 95**

Reproduced by permission of: **DEUTERON SOURCE**

Radiation Laboratory  
University of California



ELECTRIC FOCUSING EFFECT ON IONS IN A CYCLOTRON. THE FIGURE ILLUSTRATES THE POTENTIAL DISTRIBUTION IN THE GAP BETWEEN DEES. ASSUMING THE VOLTAGE TO BE CONSTANT DURING TRAVERSAL OF THE GAP, AN ION OUTSIDE OF THE MEDIAN PLANE IS DEFLECTED TOWARD THE PLANE OVER HALF THE GAP AND AWAY FROM THE PLANE IN THE SECOND HALF. THE NET EFFECT IS FOCUSING SINCE THE TRANSIT TIME IS SHORTER IN THE SECOND HALF DUE TO THE INCREASED VELOCITY.

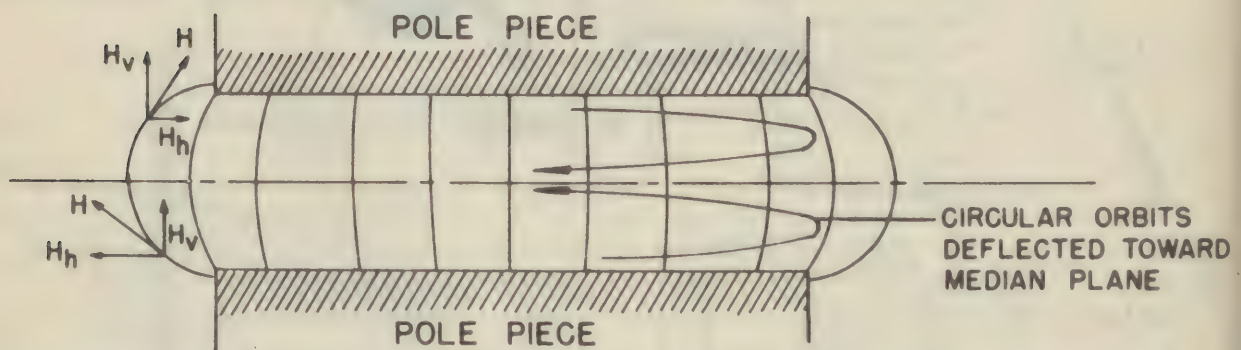


Fig. 96 MAGNETIC FOCUSING EFFECT ON ION PATHS OF LARGE RADIUS IN THE CYCLOTRON. BOWING OF THE MAGNETIC FIELD NEAR THE EDGE PROVIDES A HORIZONTAL COMPONENT IN THE FIELD WHICH DEFLECTS PARTICLES TOWARD THE MEDIAN PLANE.



## II. MEASUREMENT OF ISOTOPES

### 18. GEIGER-MÜLLER COUNTERS

#### A. General Properties

Geiger-Müller tubes are a form of high gain, gas filled, amplifying diode operated at potentials below the continuous discharge voltage. Its essential function is that of a triggering device in which a discharge is initiated by an ionizing particle. The subsequent accumulation of negative charge, reaching a magnitude of the order of  $10^{-8}$  coulomb, is collected at an anode where it can be detected as a voltage pulse by appropriate instruments. The usual form of G. M. tube consists of a cylindrical cathode with a coaxially mounted wire anode sealed in a tube containing various gas mixtures, usually at reduced pressure. Designs, materials, and gas mixtures of many varieties are used depending largely on the kind of radiation to be measured and to some extent, upon special purposes. The G. M. tubes commonly used in practice vary in size from 0.3 cm. to 10 cm. in diameter and lengths from 2 cm. to 50 cm., while for most tubes the anode wire, usually tungsten, is about 0.02 to 0.1 mm. in diameter.

The size, duration and general character of a discharge in a G. M. tube is independent of the specific ionizing power of the initial particle. Thus an electron and an alpha particle produce the same pulse as observed on an oscilloscope although the latter produces  $10^3 - 10^5$  times as many ion pairs per cm. of path. One ion pair, if formed in the sensitive region of the G. M. tube, is sufficient to trigger the discharge which subsequently involves roughly  $10^{10}$  ion pairs.

The first part of the discharge occurs rapidly. Electrons released by the initial ionizing particle drift to the central anode wire. In the high

electric field close to the wire, the electrons acquire sufficient energy between collisions to ionize the neutral gas molecules and, thus, release additional electrons which contribute to a Townsend avalanche; multiplying the initial number of electrons by a factor of  $10^8$  to  $10^{12}$ . Because of the high mobility of electrons, this part of the process is completed in less than one microsecond. The less mobile positive ions, however, remain as a positive space charge surrounding the anode along its entire length (1, 2) and the subsequent behavior of the discharge following the Townsend avalanche depends upon the form of the gas used to fill the counter; more generally, depending upon whether the gas is monatomic or polyatomic in the sense that it contains three or more atoms.

#### B. None-self Quenching Counters

When only monatomic or diatomic gases are present, the counter is said to be non-self quenching. Following the generally accepted qualitative description of the processes given by Montgomery and Montgomery (3) and other writers (4), the presence of the residual, slow moving positive ion sheath greatly modifies the electrostatic field gradient surrounding the anode, thus quenching the avalanche by preventing any remaining free electrons from acquiring sufficient energy between collisions to cause ionization. The positive ions then move to the cathode in a time of the order of  $10^{-4}$  seconds. At the cathode surface they are neutralized by ejecting an electron from the wall. This is immediately followed by the emission of one or more photons from each atom as it returns to the ground state. For some monatomic gases such as argon, helium, and hydrogen, the emitted radiation lies in the ultra violet and hence possesses



sufficient energy to eject photoelectrons from the counter walls where it is absorbed. Although the photoelectric efficiency is of the order of 1 ejected electron per  $10^4$  photons, if  $10^{10}$  ions are formed in the discharge process, the probability of electron ejection is high and consequently the discharge is continued. In addition, positive ion bombardment of the cathode at potentials normally used in operating counters frequently results in the direct ejection of free electrons which may continue the discharge. A third mechanism explained by Ramsey (5) and others occurs when the initial avalanche is small. Photons emitted by ions in the avalanche which capture an electron, before reaching the cathode, can eject photoelectrons which then maintain the discharge in what is observed to be a series of diminishing pulses.

Thus, discharges in tubes containing only mono- or diatomic gases will continue so long as the anode potential is maintained. Quenching is accomplished in such tubes only by some external device such as a high resistance; usually of the order of magnitude of  $10^9$  ohms, or by an electronic circuit which reduces the anode potential below the threshold voltage after the initial part of the pulse until the positive ions are collected. Such counters have revolving times of several times  $10^{-4}$  seconds corresponding to the transit time for positive ions.

### C. Self-Quenching Counters

The addition of polyatomic gases such as methane, alcohol, or amyl-acetate alters the process in a way to quench the discharge following the Townsend avalanche without the use of external quenching circuits and are called self-quenching counters or fast counters. The resolving times of

such counters is usually of the order of  $10^{-4}$  seconds or less.

The principle function of the polyatomic quenching gas is to prevent further production of electrons following the completion of the initial Townsend avalanche. This is accomplished mainly by reducing photoemission and secondary electron emission from the cathode walls (4).

The effectiveness of polyatomic gases in absorbing photons is due to the diffuse vibration-rotation interaction absorption bands present in the ultra violet region of the spectrum. Radiation emitted by excited argon, helium, etc., lies between 1020 Å and 790 Å and can, therefore, be absorbed by such molecules as methane and alcohol which have continuous absorption bands blanketing this region. In addition to absorbing radiation, it is equally important that such molecules do not re-emit the absorbed photons but have instead a strong tendency toward releasing the excitation energy by photodecomposition. This appears to be valid for all polyatomic gases exhibiting quenching properties.

Secondary emission is effectively reduced by two mechanisms. First, the monatomic and diatomic ions formed in the initial ionization process are prevented from reaching the wall by the process of electron exchange with neutral polyatomic molecules with which they collide with a frequency of roughly  $10^2 - 10^3$  per centimeter of path. This is possible only when the ionization potential of the quenching gas is less than that of the non-quenching gas (4). The photons emitted in the process are absorbed, in turn, by other polyatomic molecules. Second, the quenching gas ions, formed either by the initial ionizing event or by electron exchange, are neutralized by electron ejection from the wall but exhibit a greater probability for decomposition than for ejection of a free electron or radiative



capture. Altogether, the probability of secondary electron production appears to be 1 electron per  $10^{10}$  ions (6, 7) and these can be absorbed by the slow moving residual quenching gas ions.

The presence of appreciable quantities of negative ion-forming gases such as  $O_2$ ,  $H_2O$ , and the halogens in a counter considerably alters the mechanism of discharge and with it the desirable operating characteristics. The slow collection time of negative ions compared to electrons tends to prolong the discharge time and frequently leads to the complete disappearance of the Geiger-Müller plateau.

#### D. Pulse and Voltage Characteristics

Voltage pulses, observed on an oscilloscope, decrease rapidly from anode potential to a minimum value in a time of the order of one microsecond corresponding to the collection time of the electrons. Following the pulse minimum, the voltage slowly recovers to normal anode potential as the residual positive ions are swept out. During the first part of the pulse, referred to as the dead time, the counter is wholly insensitive to a second ionizing event. As the voltage recovers beyond a critical value, an ionizing event may produce a successively larger pulse until, at the termination of the recovery time, a normal pulse voltage is again produced as shown in figure 97. Both the dead time and recovery time appear to have durations of the order  $2 \times 10^{-4}$  seconds.

Voltage characteristics of counters are determined by observing the counting rate for increasing anode voltage. The important characteristics of a Geiger-Müller, or discharge, counter is the existence of a well-defined plateau voltage region over which the counting rate does not increase appreciably. Normally this region should be flat within 2 percent over an

internal of 200-300 volts.

The following voltages are frequently referred to:

Starting voltage: lowest voltage at which counts are observed. This depends largely on the detecting circuits used.

Proportional threshold voltage: lowest voltage at which proportional pulses are observed. This is often identical with the starting voltage depending upon the detecting circuits.

Geiger-Müller threshold voltage: lowest voltage at which all pulses have the same height.

Operating Voltage: the normal voltage at which a counter is operated, usually in the lower half of the plateau region.

Over voltage: the difference between the operating voltage and G. M. threshold voltage.

The voltage regions of a counter usually referred to are given below:

Region of a few volts above ground potential in which recombination of ions formed by an ionizing particle recombine before collection by the anode or cathode.

Ionization region: Usually of the order of tens of volts; initial ions are collected but do not multiply appreciably.

Proportional region: Pulse produced by an ionizing event is proportional to the initial number of ions formed for any fixed operating voltage.

Geiger-Müller transition or limited proportionality region: Pulses are no longer strictly proportional and large pulses exhibit some of the characteristics of the G. M. region.



Geiger-Müller region: Discharge characteristics in which pulse size as independent of initial ionizing event and the counting rate remains essentially constant.

Continuous discharge region: Characterized by a continuous glow discharge

#### E. Filling Gases

The most frequently used filling gas is a mixture of argon (80-95 percent) and alcohol (5-20 percent) at a total pressure of 5 to 20 cm. Hg. Argon has a large cross section for ionization, a sufficiently high ionization potential to allow electron transfer with most polyatomic molecules, does not form negative ions and is readily available. Quenching gases other than ethyl alcohol can be used, for example, ethane, amyl acetate, ethane, tetraethyl lead, etc. Heavy polyatomic molecules may be used and some increase in useful counter life will usually be found because of the greater number of decompositions required to reduce it to a non-quenching gas. However, their use in most counters is undesirable since it leads to a longer resolving time due to the low mobility of heavy ions. Gases which have strong tendencies to produce negative ions should be avoided( 4, 9). This includes primarily  $O_2$ ,  $CO_2$ , water vapor and the halogens.

Table 16. IONIZATION POTENTIALS OF COUNTER GASES (10)

Non-Quenching		Quenching	
Substance	Volts	Substance	Volts
A	15.68	CH <sub>4</sub>	14.5
N <sub>2</sub>	15.51	CS <sub>2</sub>	10.4
Ne	21.47	C <sub>2</sub> H <sub>2</sub>	11.6
Xe	12.08	C <sub>2</sub> H <sub>2</sub>	12.2
H <sub>2</sub>	15.6	C <sub>2</sub> H <sub>6</sub>	12.8
K	4.318	NH <sub>3</sub>	11.2
H <sub>2</sub> O	12.56	C <sub>2</sub> H <sub>5</sub> OH	11.3
CO	14.1		
CO <sub>2</sub>	14.4		
CN	14.0		
He	24.46		

#### F. Counting Tube Life

The useful life of self-quenching counters appears to be dependent upon the volume of gas in the counter (8). In each discharge, approximately  $10^{10}$  ion pairs are formed and a small fraction of the polyatomic molecules are decomposed into smaller fragments, some of which continue to behave as a quenching gas. Ultimately, however, an appreciable fraction of the complex molecules are reduced to free oxygen, hydrogen, and carbon which remain in part as non-quenching gases, and in part as an accumulation of crud on the cathode. The counter is then no longer self-quenching and must be refilled. Assuming  $10^8 - 10^{10}$  quenching gas molecules decomposed



per discharge, and a total number of  $10^{20}$ , the approximate life of a counter is the order of  $10^{10}$  counts. The effective life can be prolonged somewhat by operating the counter at a voltage in the lower end of the plateau and by increasing the gas volume. The latter method has been successfully employed for very small counters by attaching a bulb of larger dimension to the counter outside of the sensitive region to serve as a reservoir (8).

#### G. Gas Counters

A higher order of sensitivity as compared with the thin window counter can be attained in measuring the activity of very low energy beta emitting substances by introducing the isotope in some gaseous form into the counter as part of the filling gas. This is particularly useful for measurements of weak activities of  $C^{14}$  and for all activities of  $H^3$  which have maximum energies of 145 kev and 15 kev respectively. In principle, any radioactive isotope which can be put in a gas form can be measured by this means. If the maximum energy is greater than .2 mev or if gamma rays are emitted, a procedure using a thin window gamma counter is, in general, faster and more convenient.

#### H. $H^3$ Gas Counter

Beta emitters with maximum energies as low as tritium (15 kev) must necessarily be measured under conditions which avoids any absorber including self absorption. This is possible in G. M. tubes only by introducing the tritium directly into the sensitive region of the tube. Satisfactory procedures of this kind have been developed by Black and Taylor (11), Pace (12), Allen (13), and Cornog (14) in which tritium is introduced as part of the gas filling mixture in the form of HTO vapor. A conventional design

of glass walled tube is used which has a total volume of 1 litre , a 5 cm diameter copper-screen cathode, and a 0.010 inch diameter tungsten anode.

The disturbing effects of water vapor in G. M. tubes are avoided by limiting the H<sub>2</sub>O vapor pressure in the tube to 2 mm Hg. To this is added a mixture of 2.5 cm. Hg. of anhydrous ethyl alcohol and 2 cm Hg of argon. Immediately after filling, the counting rate increases and reaches a constant value after approximately 30 minutes. The counting rate has been found to be linear for activities up to 3600 cpm for the tube described here. At higher counting rates, the response is not linear and dilutions must be made or calibration curves employed.

A plateau of 300 volts and a threshold of approximately 1200 volts are reported for this tube by Pace (12).

Memory effects due to adsorption of water vapor are considerably more serious than for most other substances except H. However, a procedure suggested by Pace reduces the counting rate to normal background after a sample measurement. Between samples the tube is alternately evacuated and flushed with inactive water vapor eight times and followed by an air rinse and finally evacuation to 0.3 micron.

### I. Cl<sub>4</sub> Gas Counter

A successful type of gas counter for measuring Cl<sub>4</sub> in the form of CO<sub>2</sub> has been developed by Miller (15). A conventional gamma G. M. tube is constructed of either metal or glass with a 0.006 inch diameter tungsten anode and, in the glass tubes, a chemically deposited silver cathode coated with aqua dag. Carbon dioxide containing the Cl<sub>4</sub> is introduced at pressures from 10-50 cm Hg. Satisfactory G. M. characteristics are obtained by



the addition of 2 cm of  $\text{CS}_2$  which provides a 200 volt plateau with a 2 per-cent slope. The threshold voltage varies from 1800 to 4500 depending upon the cathode diameter (1-4 cm) and the gas pressure. The optimum operating voltage was found to approximately 160 volts above threshold voltage.

Two corrections must be made when these tubes are used for measurement of absolute disintegration rates. The first is the counting loss at high counting rates, i.e., of the order of 10,000 cpm, which may be made from a calibration curve for each counter determined from samples of known relative activity. The second empirical correction is a geometrical factor resulting from the insensitive volume of the counter and defined as the ratio of the total counter volume  $V_0$  to the sensitive volume defined by the cathode  $V_1$ . The true activity,  $N$  of a sample in which  $N_0$  cpm is observed, is then  $N = CN_0V_0/V_1$ , where  $C$  is the counting correction factor from the calibration curve.

Memory effect appears to be negligible for  $\text{CO}_2$ .

### J. Neutron Counters

Counters intended for the direct detection of neutrons depend upon either the recoil of light nuclei from the filling gas, or on the charged particles emitted in nuclear interactions with the material of the counter wall or filling gas. The choice between these two mechanisms and the materials of the counter depend upon the energy range of the neutrons to be detected. In most applications, neutron counters are operated in the proportional region in order to reduce the less heavily ionizing background of gamma and electron radiation. This is essential for measuring low-neutron flux since the efficiency for neutrons is usually small

compared with that for incident charged particles.

### K. Slow Neutron Counters

Slow neutrons are usually detected by interaction with  $B_{10}$  nuclei according to the reaction  $B_{10}(n,\alpha)Li^7$ . The reaction is accompanied by the release of 2.5 mev of which 1.6 mev is contributed to the  $\alpha$  particle and 0.9 mev to the recoil lithium nucleus. If both particles are absorbed by the filling gas, roughly 75,000 ion pairs are formed, assuming an average energy loss of 33 ev per ion pair. Boron can be used in proportional counter either as the filling gas in the form of  $BF_3$  (16) or as a thin coating of metal on the cathode wall.

Boron trifluoride filled counters are constructed similar to gamma counters, preferably with materials which do not have large thermal-neutron capture cross-sections, e.g., boron glass, and filled to a pressure of 10-760 mm Hg. The maximum pressure which can be used is limited by both the increase in the operating voltage and increased size of electron pulses, and the lowest pressure is determined by the neutron counting efficiency desired.

The efficiency of the counter, defined as the probability that a neutron traversing an average length  $l$  through the counter is captures, is given by, (6),

$$\epsilon = lrpL\sigma_v$$

$p$  = pressure.

$L$  = Loschmidt's number.

$r$  = isotope concentration,  $B_{10}/(B_{10} + B_{11})$ .

$\sigma_v$  = cross section for neutron of velocity  $v$ .



The neutron capture cross section of B11 is negligible compared to B10 and does not contribute appreciably to the neutron count. Higher counting efficiency can, therefore, be attained by increasing the enhancement of B10 above its natural fractional concentration of 0.18 (17). The efficiency also varies with the neutron energy since  $\sigma \sim 1/\sqrt{E}$ . Within the experimental accuracy, the cross for energies between 0.01 and 10,000 ev is given by

$$\sigma_v = \frac{114}{\sqrt{E}} - 0.20$$

Neutron counters with boron coated cathodes are usually filled with standard argon-alcohol mixtures and operated at voltages within the proportional region for the particular counter. The thickness of the boron layer on the cathode should not be made greater than the range of the alpha particle ejected from a boron nucleus by a slow neutron, i.e., 0.1 mm. Greater thicknesses will not increase the efficiency, but rather, lead to excessive absorption of neutrons since a larger fraction of the ejected alpha particles will not reach the sensitive volume of the counter. The maximum efficiency of such counters is given by

$$E = \frac{p \sigma_v R N}{A} \quad (6)$$

$p$  = boron density.

$N$  = Avogadro's number.

$A$  = atomic weight.

$R$  = alpha particle range in boron.

$\sigma_v$  = boron cross section for energy  $E$ .

In a similar way, a very thin layer of uranium may be used instead of boron. The fission products resulting from the absorption of slow neutrons produce heavy ionization but if most of their range lies within the uranium layer they cannot be distinguished from the alpha particles due to the natural uranium decay and must, therefore, be treated by the usual statistical method for background counts. The normal fractional concentration of the effective isotope,  $U^{235}$ , is 0.71 and has a cross section  $\approx 550$  for .025 ev neutrons.

### L. Fast Neutron Counters

Detection of fast neutrons with proportional counters is accomplished most effectively by the recoil of light nuclei from elastic collisions. The maximum energy transferred from the neutron to the struck nucleus is

$$E = E_0 \frac{4M}{(M+1)^2}$$

$M$  = mass of nucleus in units of neutron mass.

$E_0$  = neutron energy.

$E$  = recoil energy of nucleus.

and the average energy is approximately

$$E_{av.} = E_0 \frac{4M}{3(M+1)^2}$$

If hydrogen is used for the filling gas, the maximum recoil proton energy, due to a head-on collision, is equal to the full neutron energy.

If the smallest detectable pulse is produced by a recoil energy  $B_0$ , referred to as the bias energy, the lowest energy neutron which can be detected is  $B = B_0/E$  (18). For hydrogen, the cross section for neutron



energies above 0.050 mev varies as  $1/E^{\frac{1}{2}}$ , and therefore, the sensitivity of hydrogen filled counters varies approximately as

$$E^{-\frac{1}{2}} (1 - \frac{B}{E})$$

The sensitivity rises rapidly for neutrons with greater than the bias energy and then remains relatively constant in the energy interval  $1.57B < E_0 < 9.6B$ . The existence of a threshold is an important property of the hydrogen-filled proportion counter. An alternative form of proton recoil counter employs thin hydrogenous radiators mounted within the counter tube (18, 19). Radiators are frequently prepared by the evaporation of glycerol tristearate on thin platinum discs in a vacuum. Thickness is usually of the order of 100 mg. per  $\text{cm}^2$ . The same characteristics are observed as for hydrogen filled counters provided the filling gas has a sufficiently high stopping power to stop all hydrogen recoils within the gas volume and does not itself recoil with greater than the bias energy. Heavy inert gases such as argon, krypton, xenon, etc., are the most satisfactory for this reason.

The elastic scattering cross section of hydrogen and most other substances for fast neutrons is of the order of one barn; hence the efficiency of counters used in this energy range is necessarily low. In addition to counts from recoil nuclei, counts will be registered from competing neutrons processes occurring in the counter wall or in filling gases other than hydrogen, from which proton, deuteron, alpha particle, and gamma ray may be liberated. The cross sections for these interactions in nearly all substances is also of the order of one barn. Thus, if a  $\text{BF}_3$  counter is used for detecting very fast neutrons, discharges are initiated by alpha particles from the reaction  $\text{B}(n, \alpha)\text{Li}$  as well as by recoil B and F nuclei.

### M. Accuracy of Counting Measurements

An estimation of the accuracy of counting measurements on the activity of a sample is determined, for the most part, by simple statistical procedures. The statistical methods employed is based upon the fact that each disintegration is a statistically independent event since it is in no way affected by a preceding event or the means by which it is detected. The distribution of disintegrations in time and the fraction detected is then purely random. In a time,  $t$ , which is small compared to the half-life of the substance, the probability,  $P$ , of observing  $n$  particles is given by Poissons law for random distributions (20).

$$P = \frac{\bar{n}^n}{n!} e^{-\bar{n}}$$

where  $\bar{n}$  is the average number of particles detected per unit time.

Aside from the intrinsic form of the distribution of the data to be expected, the important facts concerning a set of measurements are estimations of reliability in terms of the variability of the data. Three measures of variability are commonly used for this purpose; average deviation from the mean, standard deviation from the mean, and the probable error. Of these, the probable error is used almost exclusively for estimating the statistical error in counting measurements.

### N. Average deviation

If  $\bar{n}$  is the average number of counts per unit time for  $M$  measurements with the same sample under identical physical conditions, the average deviation from the mean value is

$$A.D. = \frac{\sum_{i=1}^M \left| \bar{n} - \frac{n_i}{t_i} \right|}{M}$$



This formula may be applied when counting by predetermined time intervals,  $t_i$ , or by predetermined count number intervals,  $n_i$ , or by arbitrary choice of both.

#### 0. Standard deviation.

The standard deviation from the mean,  $\sigma$ , is defined as the root mean square of the sum of the deviations from the mean:

$$\sigma = \sqrt{\frac{\sum_{i=1}^M \left| \bar{n} - \frac{n_i}{t_i} \right|^2}{M}}$$

Also, from Poisson's formula, a more convenient form is generally used when a single measurement of  $N$  total counts is taken over a time  $t$ :

$$\sigma = \sqrt{\bar{n} t} = \sqrt{N}$$

If several sets of measurements are taken, the resulting standard deviation is

$$\sigma = \sqrt{\sum_{i=1}^M \sigma_i^2}$$

The error in any counting measurement must necessarily include the standard deviation of the background count,  $\sigma_b$ , as well as of the sample,  $\sigma_s$ , given by

$$\sigma = \sqrt{\sigma_b^2 + \sigma_s^2} = \sqrt{N_b + N_s} = \sqrt{N}$$

where  $N$  is the total number of counts; background plus sample.

#### P. Probable Error.

The probable error,  $r$ , is calculated from the standard deviation,  $\sigma$ , or directly from the total number of counts of the sample plus background,  $N$ , and the total background count  $N_b$  counted for the same length of time. The probable error in counts is

$$r = 0.6745 \sigma = 0.6745 \sqrt{N + N_b}$$

In terms of percent:

$$r \% = \frac{67.45}{(N - N_b)} \sqrt{N + N_b}$$

It defines limits,  $\pm r$ , about the mean value,  $\bar{N}$ , within which the real value of the activity should occur with a probability of .5, and with an equal probability for all values outside these limits.

When the approximate values of the sample and background counting rates are known, it is frequently more convenient to count samples by time intervals rather than by total events. When the sample plus background and the background are counted separately to give the same relative probable error, the minimum time required to reduce the total statistical error of the sample measurement to a prescribed percentage,  $r$ , is given by

$$t = \frac{9,100 \bar{N}}{r^2 (\bar{N} - \bar{N}_b)^2}$$

and for the background, the minimum counting time should be



$$t_b = \frac{(\bar{N} - \bar{N}_b)^2 t}{\bar{N} \bar{N}_b}$$

$\bar{N}$  = average counting rate of sample plus background.

$\bar{N}_b$  = average counting rate of background.

The true value of  $\bar{N} - \bar{N}_b$  is then calculated with the prescribed accuracy from the total counts  $N$  in the time  $t$  and background counts  $N_b$  in the time  $t_b$ .

When possible, lead shielding should be used to reduce the magnitude of the background counting rate and hence the required counting time.

#### Q. High Counting Rate Losses

Significant errors are introduced into measurements involving counting rates over several thousand per minute. Such errors arise from the finite resolving time of the counting tube ( $\sim 10^{-4}$  sec.) and possibly from the resolving times of the amplifier, scaling circuit and recording meter if any of these is larger than that of the counting tube. Complete calculations of the corrections which could be applied are difficult and usually unnecessary since the recovery time of the G. M. tube is generally not known more accurately than 10 percent. Several elementary corrections can be made, however, when an accuracy of the order of a few percent is anticipated for counting rates of several thousand per minute.

The simplest procedure is the construction of a calibration curve for a particular tube and its associated circuits. Standards of known relative strength with identical dimensions and self-absorption will provide a correction curve by plotting the relative source activity against the observed counting rate.

Calculations of the counting loss may be made under the simplified

conditions given below.

a. The recovery time of the G. M. tube,  $T$  sec, is greater than any other component of the counting circuit, i.e., amplifier, scaling circuit or recording meter. The recovery times of these components will then not influence the counting rate. If  $n$  particles are counted in a time,  $t$  sec., the number of particles,  $n_0$ , which actually passed through the sensitive region of the tube is given by the approximate formula

$$n_0 = \frac{n}{1 - n(T/t)}$$

This formula may be used when the average number of incident particles in the time  $T$  is less than 1, or  $t/n < T$  (21, 22, 23).

b. The recovery time,  $T_1$ , of some component of the counting system is greater than the recovery time of the G. M. tube. Both recovery times then contribute to the counting loss. An exact calculation of the error is impracticable but the upper limit to be expected is given by

$$n_0 = \frac{t^2}{nT^2} \left( 1 - \frac{nT_1}{t} - \sqrt{\left(1 - \frac{nT_1}{t}\right)^2 - 2n^2 \frac{T^2}{t^2}} \right)$$

It is assumed in the application of this formula, that the resolving time of each component of the electrical circuit and recorder is constant and, in particular, independent of pulses which may arrive from the G. M. tube during the time the circuit is recovering from a preceding pulse. In certain types of circuits this assumption is not valid. The occurrence



of a pulse during recovery will, in this instance, further extend the recovery by an interval equal to the resolving time of that component. When this mechanism effects the counting, the relation between the true and the observed counts,  $n_0$  and  $n$  respectively, in a time  $t$  is

$$n = n_0 e^{T_1/t}$$

At very high counting rates, i.e.,  $n_0 > \frac{t}{T_1}$ , the counting circuit becomes effectively blocked and  $n \rightarrow 0$ . At low counting rates,  $n_0 \ll \frac{t}{T_1}$ , the difference between this and the preceding formula is negligible. However, if  $T_1 < T$ , this mechanism does not affect the counting rate and formula in section Q should be used.

#### R. Counter Resolving Time

The shortest interval in which two successive particles can produce separate discharges in a G. M. tube is variously known as the recovery time, dead time, or insensitive time. For most counting tubes the recovery time is of the order of  $10^{-4}$  seconds or approximately the collection time of the positive ions formed in the discharge. A standard procedure for the determination of the response time is based on an estimate of the observed counting loss when counting two sources of nearly equal counting rate separately and together. The resolving time is given by

$$T = \frac{(n_1 + n_2 - n_{12})}{n_{12}(n_1 + n_2)} t$$

$n_1$  = total recorded counts of sample 1 in time,  $t$  sec's.

$n_2$  = total recorded counts of sample 2 in time,  $t$  sec's.

$n_{12}$  = total recorded counts of sample 1 2 in time,  $t$  sec's.

The counting time should be sufficiently long to provide a small probable error since the recovery time is estimated from small differences of large numbers. The resolving time calculated by this procedure is the true time for the G. M. tube only if the recovery time of each of the other components of the counting circuit is smaller. If any component has a longer time,  $T_1$ , the measured value is a function of both  $T$  and  $T_1$  and the value calculated is somewhat greater than the true resolving time of the G. M. tube.

### S. Coincidence Counting Corrections

#### 1. Accidental Coincidence Counts

As in the case of single counters, coincidence counting measurements must be corrected for background, in this case, only of accidental coincidence counts. Such counts may be produced by the simultaneous arrival of several related particles as in cosmic ray showers or by the chance arrival of two independent particles in a time of the order  $2T$  due to a high radiation level such as exists near high energy accelerators. The number of accidental counts per second to be expected from a two fold coincidence arrangement is

$$m = 2\bar{n}_1\bar{n}_2T$$

$\bar{n}_1, \bar{n}_2$  = average counts per second independently from counters 1 and 2.

$T$  = recovery time of counters in seconds.

For an  $r$ -fold coincidence arrangement, assuming the recovery times are equal, the accidental counting rate is

$$m = rT^{r-1}(n_1n_2 \dots n_r)$$



If the resolving times are different for each of the counters of an  $r$ -fold coincidence set, (24);

$$m = n_1 n_2 \dots n_r T_1 T_2 \dots T_r \left( \frac{1}{T_1} \frac{1}{T_2} \dots \frac{1}{T_r} \right)$$

If the radiation density is not high, the accidental rate can be determined by dispersing the counters and counting the coincidences. Alternatively, the accidental rate can be made negligibly small by increasing the multiplicity of the system and by reducing the counter recovery time. Accidentals may be further reduced by the proper use of anti-coincidence counters; however, their use decreases the counting efficiency because of the finite recovery time.

## 2. Counting efficiency

Aside from the counting loss due to the finite recovery time, not all particles traversing a counter will produce discharges. The efficiency of a counter to respond to incident particles can be determined with a three or higher-fold coincident arrangement by counting coincidences with and without the counter as a part of the system. The counter efficiency is then given by

$$E = \frac{N_r - m_r}{N_{r-1} - m_{r-1}}$$

$N_r$  = total counts in time  $t$  (or counting rate) of  $r$ -fold coincidence arrangement, i.e., with tested counter included.

$N_{r-1}$  = same but with tested counter removed.

$m_r$  = accidental counts in time  $t$  (or counting rate) for  $r$ -fold coincidence arrangement.

$m_{r-1}$  = accidental counts without tested counter.

With the efficiency of each counter known, the total efficiency of an r-fold coincidence arrangement is

$$E_t = E_1 E_2 \dots E_r$$

#### T. Counting Rate Meter

The counting rate meter is a circuit developed for the purpose of providing an output, usually a d.c. voltage, which is proportional to the average rate of incidence of random or periodic pulses (25, 26, 27, 28). A successful counting rate meter circuit is shown in figure 102, and described in principle below (29, 30).

Amplified pulses from a counter are fed into a conventional multivibrator which serves as a pulse equalizer by providing an output pulses uniform in size and shape and positive in polarity for each input pulse. The equalized pulses are then impressed on the grid of the vacuum tube of the integrating circuit which contains a resistive-capacitive tank circuit in series with its plate. The d.c. voltage developed across the RC circuit is found to be proportional to the average pulse rate and, hence, a vacuum tube voltmeter included in the circuit may be calibrated directly in terms of average counting rate. Alternatively, automatic recording devices can be inserted when continuous records are desirable.

In principle, the integrating circuit establishes an equilibrium voltage across the RC tank circuit directly proportional to the counting rate and in a time which is long compared to the interval between counts. Equilibrium is reached when the charge leakage rate through a high resistance across a con-



denser is equal to the rate of charge added by the pulses. In general, equilibrium is reached after several RC, or starting from zero time, it is given by (6)

$$t_0 = RC(\frac{1}{2} \log 2nRC + 0.394)$$

$n$  = pulses per unit time.

The statistics of this type of counting rate meter depends on the fact that the reading at any instant is influenced by all previous pulses weighted exponentially according to their elapsed time. The probable error of a single reading is given by (6)

$$P_1 = 0.6745 (2n RC)^{-\frac{1}{2}}$$

or in terms of percentage

$$P_1 \% = 100 \frac{P}{n}$$

If a continuous record is made, the probable error may be considerably reduced. From a record taken continuously over a time,  $T$ , the value of  $n$  is determined by drawing a line through the trace which divides the fluctuations into equal areas on both sides. The probable error in percent is then, (6),

$$P \% = \frac{100 w}{2.3 n} \frac{(1 + 2T/RC)^{\frac{1}{2}}}{(1 + T/RC)}$$

$w$  =  $\frac{1}{2}$  width of ink recorded trace.

## References

1. Stever, H. G., *Phy. R.* 61, 38 (1942)
2. Wilkemmy, M. H. and Kanne, W. R., *Phy. R.* 62, 534 (1942)
3. Montgomery, C. G. and D. D., *Phys. R.* 57, 1030 (1940)
4. Korff, S. A. and Present, R. D., *Phys. R.* 65, 274 (1944)
5. Ramsey, W. E., *Phys. R.* 57, 1022 and 1061 (1940)
6. Korf, L. A., *Electron & Nuclear Counters*, D. Van Nostrand (1946)
7. Olephant, M. L. and Moon, P. B., *Proc. Roy. Soc.* A127, 388 (1930)
8. Strajman, E., *Rev. Sci. Inst.* 17, 232 (1946)
9. Montgomery, C. G. and D. D., *Rev. Sci. Inst.* 18, 411 (1947)
10. *From Handbook of Physics and Chemistry* (1946)
11. Black, J. F., and Taylor, H. S., *J. Chem. Phys.* 11, 395 (1943)
12. Pace, N., Kline, L. *Naval Medical Research Institute, National Naval Medical Center, Bethesda, Md. Proj. X-191, No. 5* (1946)
13. Allen, M. G., and Ruben, S. J., *J. Am. Chem. Soc.* 64, 948 (1942)
14. Carnog, R. and Libby, W. F., *Phys. R.* 54, 1046 (1941)
15. Miller, W. W., *Science* 105, 123 (1947)  
*Rev. Sci. Inst.* 18, 496 (1947)
16. Korff, S. A. and Danforth, W. E., *Phys. R.* 55, 980 (1939)
17. Watson, W. W., Buchanan, J. O. and Edder, F. K. *Phys. R.* 71, 887 (1947)
18. Barschall, H. H. and Bethe, H. A., *Rev. Sci. Inst.* 18, 147 (1947)
19. Coon, F. H. and Nobles, R. A., *Rev. Sci. Inst.* 18, 44, (1947)
20. Bateman, H., *Phil Mag.*, 20, 704 (1910)
21. Ramsey, W. E., *Phys. R.* 57, 1022 (1940)
22. Montgomery, C. G. and Montgomery, D. D., *Phys. R.* 57, 1030 (1940)



23. Kurbatov, V. D. and Mann, H. B., Phys. R. 68, 40 (1945)
24. Eckart, Carl, and Shonka, F. R., Phys. R. 53, 752 (1938)
25. Curtiss, L. F. and Brown, B. W., Nat. Bur. Stand. J. Res. 34, 53 (1945)
26. Curtiss, L. F., Nat. Bur. Stand. J. Res. 23, 137 (1939)
27. Ginrich, N. S., Evans, R. D., and Edgerton, H. E., Rev. Sci. Inst. 7, 450 (1936)
28. Evans, R. D., and Alder, R. L., Rev. Sci. Inst. 10, 332 (1939)
29. Kip, A., Bousquet, A., Evans, R. and Tuttle, W. Rev. Sci. Inst. 17, 323 (1947)
30. Kip, A. F. and Evans, R. D., Phys. Rev. 59, 920A (1941)

See also the following references on counting statistics:

Bateman, H., Phil. Mag. 20, 704 (1910)

Strong, J., et al, Procedures in Experimental Physics (1941) New York

Keston, A. S., Rev. Sci. Inst. 14, 293 (1943)

Schiff, L. I., Phys. Rev. 50, 88 (1936)

Gnedenko, B. V., J. Exper. Theor. Phys. USSR 11, 101 (1941)

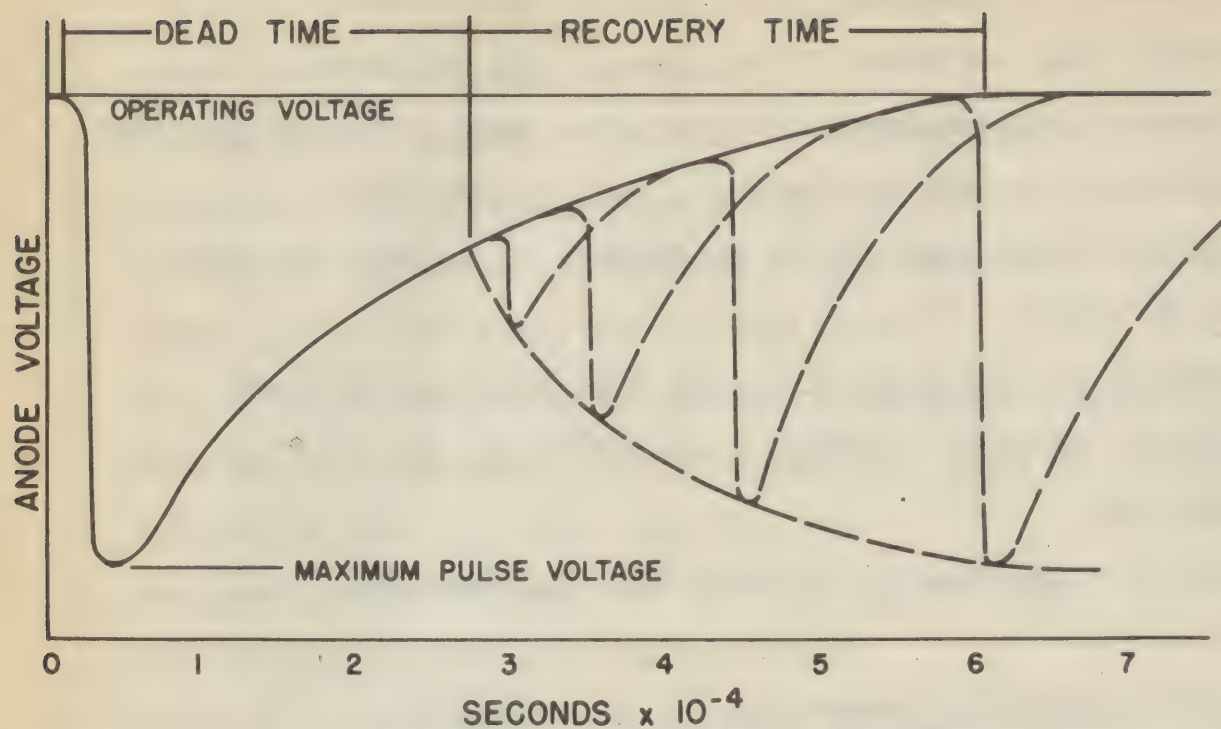
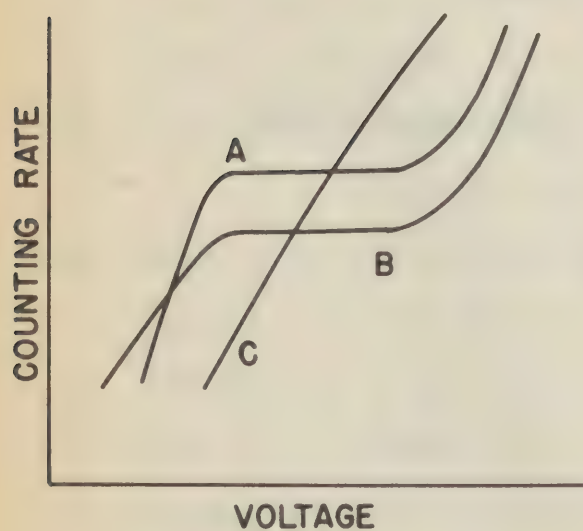


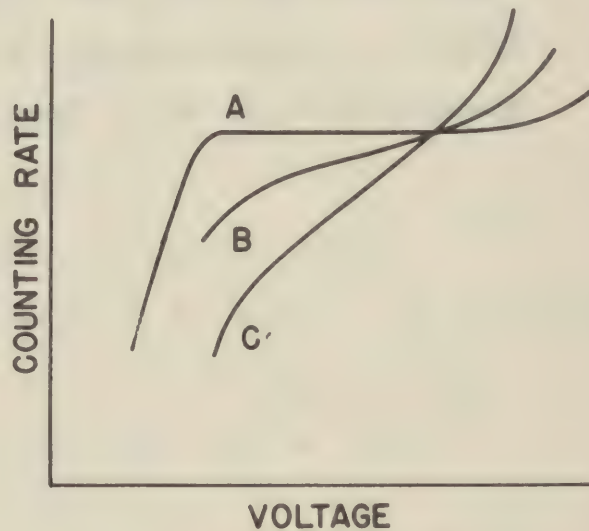
Fig. 97

### COUNTER PULSE CHARACTERISTICS

STEVEY, H.G., PHYS. REV., 61, 38 (1942)



- A. PURE METHANE
- B. 1.5 cm. ARGON ADDED
- C. 1.5 cm. H<sub>2</sub>O ADDED

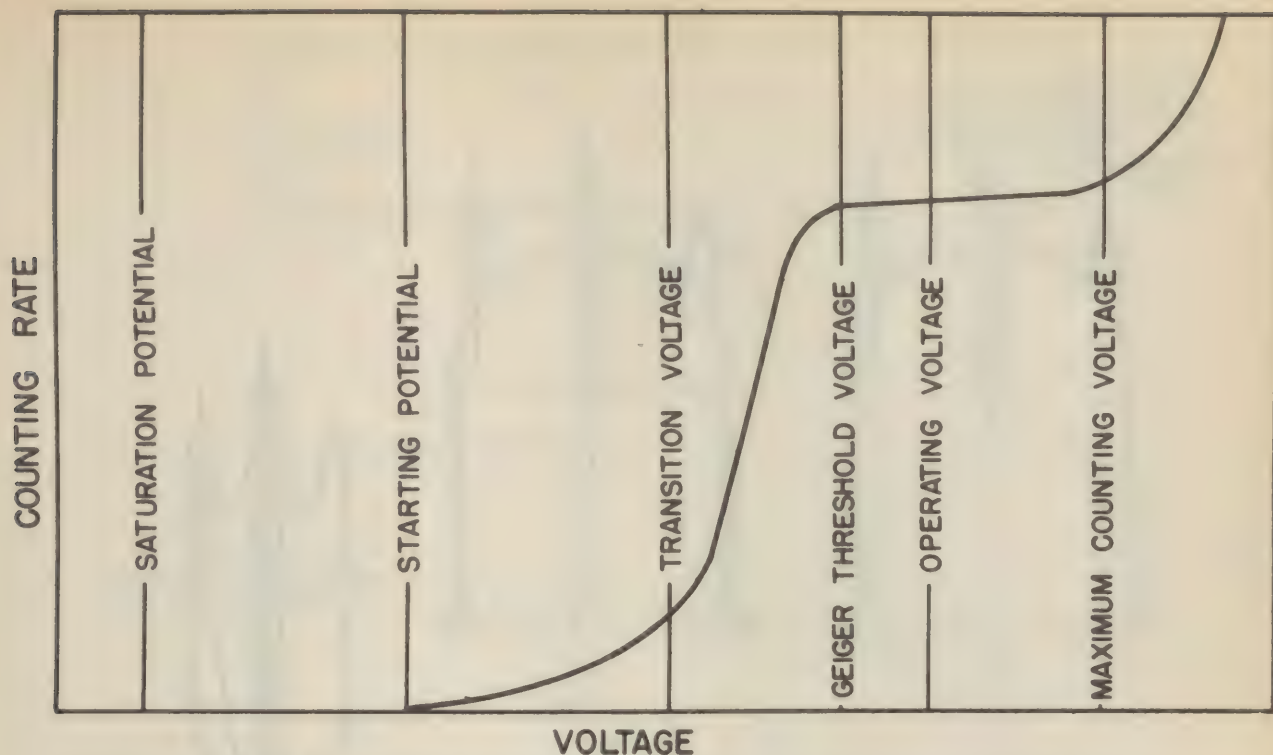


- A. PURE METHANE
- B. 1.5 mm. AIR ADDED
- C. 6.0 mm. AIR ADDED

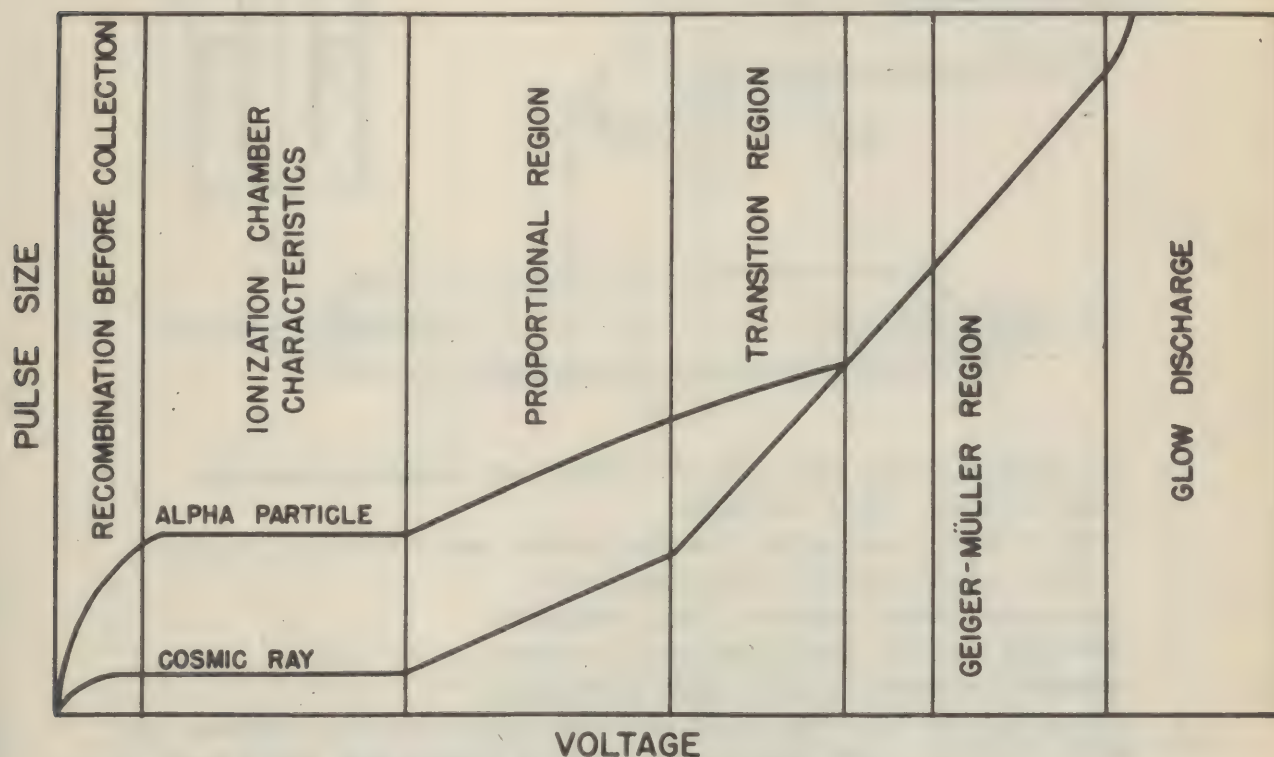
Fig. 98 EFFECTS OF GASES ON G-M PLATEAU

KORFF, S.A., & PRESENT, R.D., PHYS. REV., 65, 274 (1944)





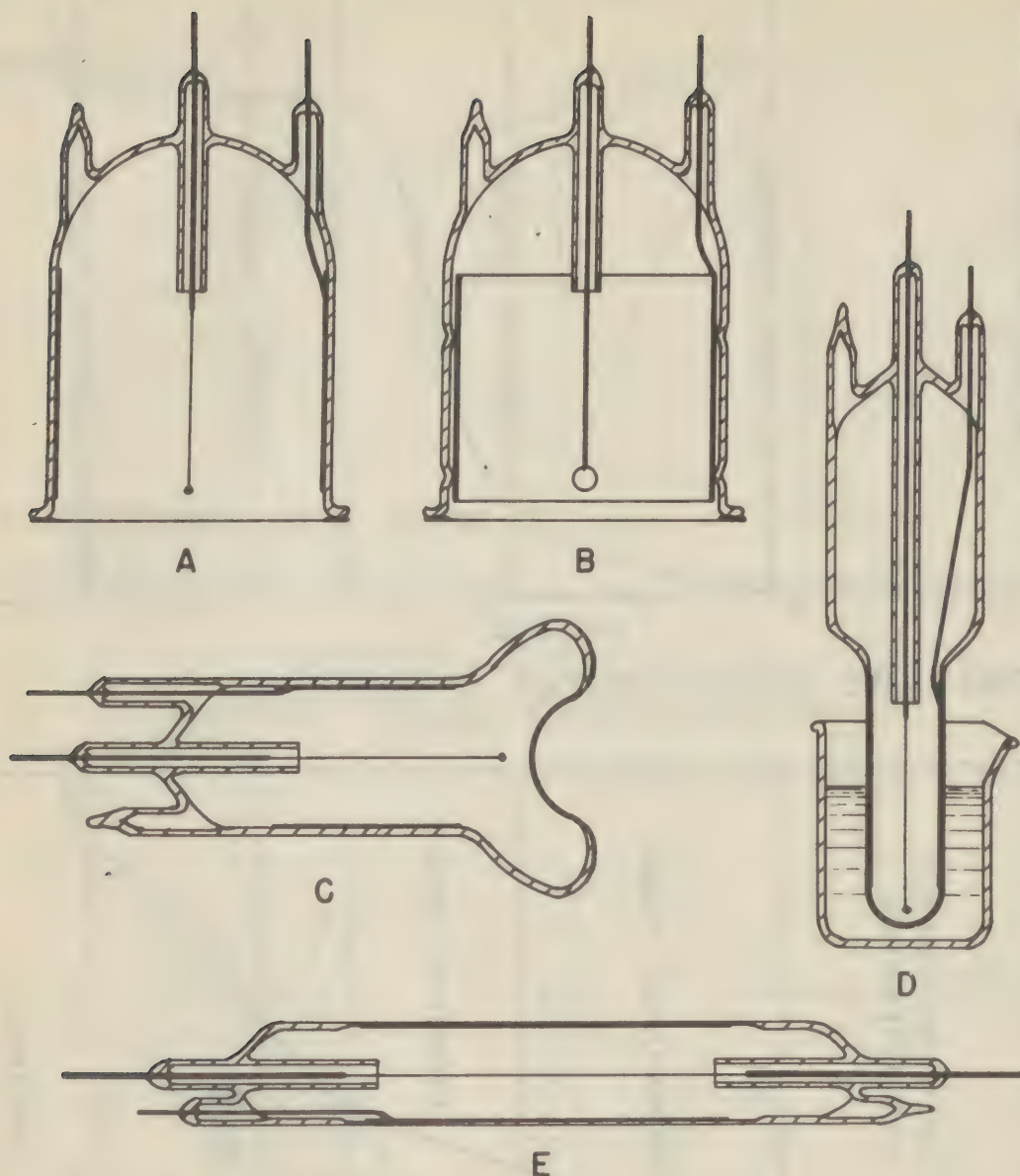
COUNTING RATE CHARACTERISTICS OF COUNTERS



PULSE SIZE CHARACTERISTICS OF COUNTERS

Fig. 99

MONTGOMERY, C. G., & MONTGOMERY, D. D., J. FRANKLIN INST., 231, 447 (1941)

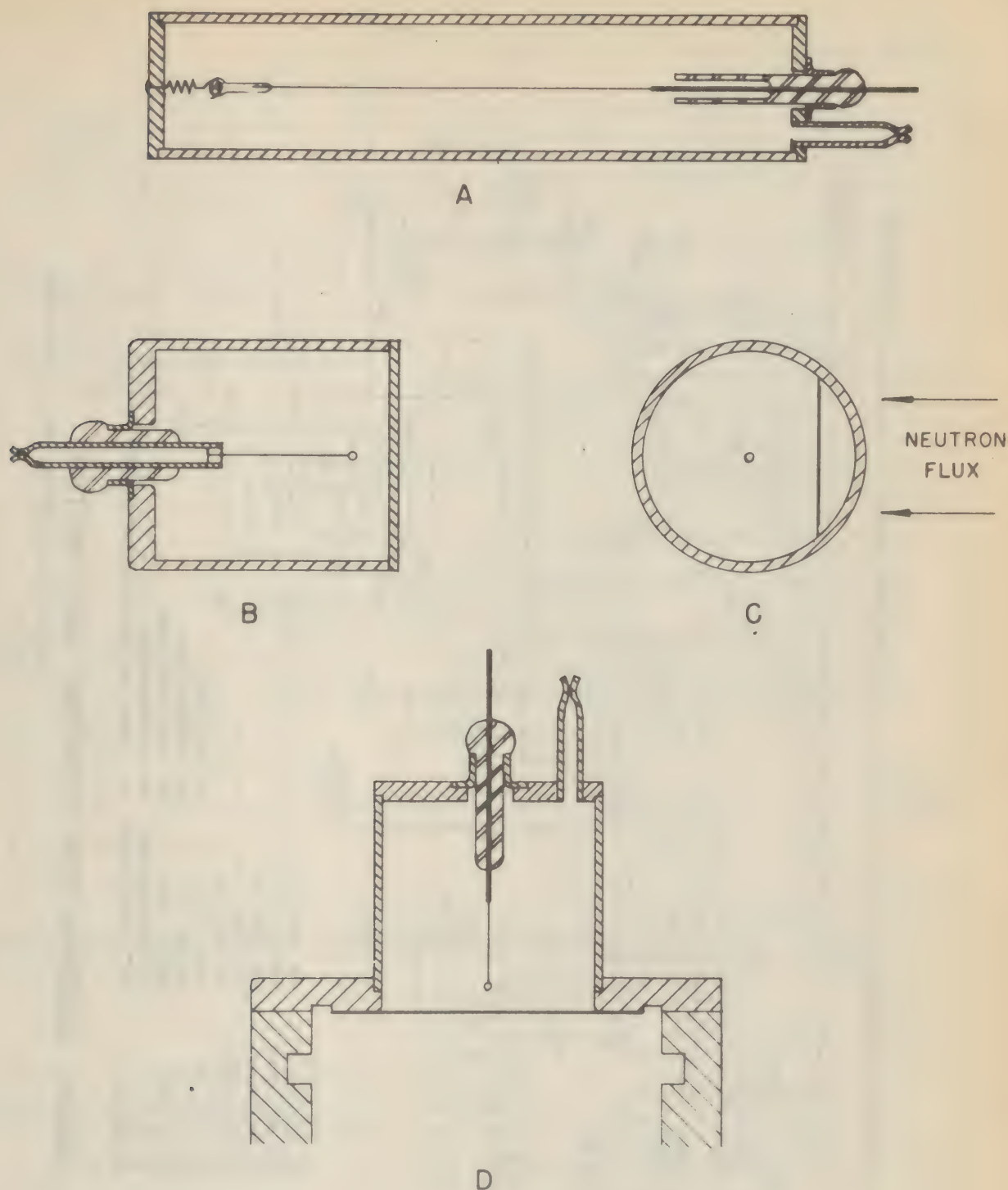


- A. BELL COUNTER. WIRE ANODE, THIN MICA WINDOW, AND CHEMICALLY DEPOSITED SILVER CATHODE. (BETA PARTICLES)
- B. POINT COUNTER. BALL ANODE, THIN MICA WINDOW, AND ALTERNATIVE INSERTED COPPER CYLINDER CATHODE. (BETA PARTICLES)
- C. THIN GLASS WINDOW COUNTER. (BETA PARTICLES)
- D. IMMERSION COUNTER. THIN GLASS WALL, DEPOSITED SILVER CATHODE. SHOWN IMMERSSED IN SAMPLE LIQUID. (BETA PARTICLES)
- E. CYLINDRICAL COUNTER. THIN GLASS WALL AND DEPOSITED SILVER CATHODE FOR BETA PARTICLES. HEAVY WALL AND COPPER MESH CATHODE FOR GAMMA RAYS.

Fig. 100 TYPICAL COUNTER TUBE DESIGNS



Fig. 101 METAL COUNTING TUBE DESIGNS



- A. CYLINDRICAL BRASS OR COPPER TUBE COUNTER USING KOVAR SEALS (COSMIC RAYS, GAMMA RAYS, NEUTRONS)
- B. COPPER "BELL" COUNTER WITH KOVAR SEAL PUMP OUT AND LEAD (GAMMA RAYS, NEUTRONS)
- C. ARRANGEMENT OF RADIATOR IN NEUTRON COUNTER. HYDROGENOUS LAYER COATED ON THIN PLATINUM PLATE.
- D. BELL COUNTER WITH MICA WINDOW AND WITH MOUNTING FOR STANDARD SAMPLE POSITION (BETA PARTICLES)

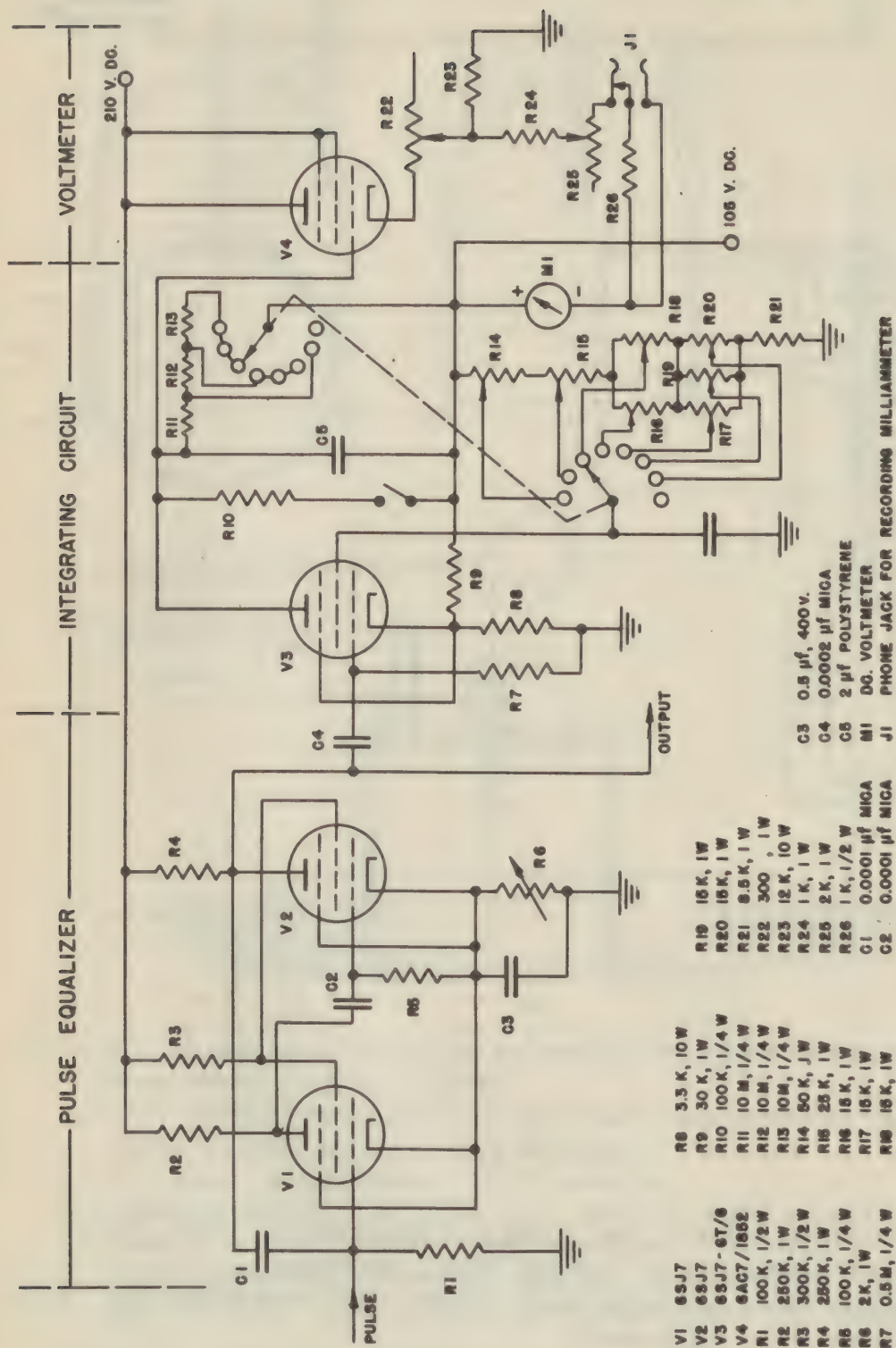
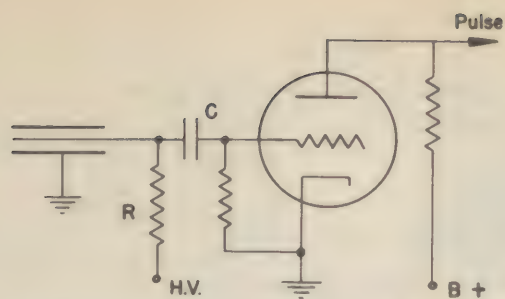


Fig. 102

CIRCUIT DIAGRAM FOR COUNTING RATE METER

KIP, A., ET AL, REV. SOL. INST., 17, 323 (1947)

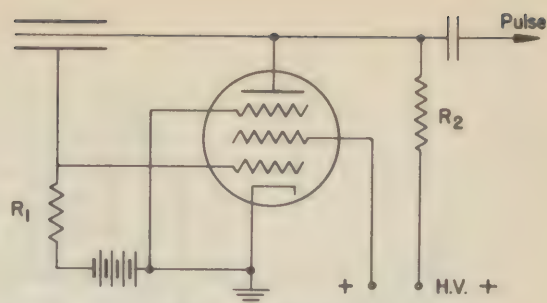




### RESISTANCE CIRCUIT

R  $10^7 - 10^9$  ohms

C Approximately  $2 \mu\text{f}$ , insulated for high voltage



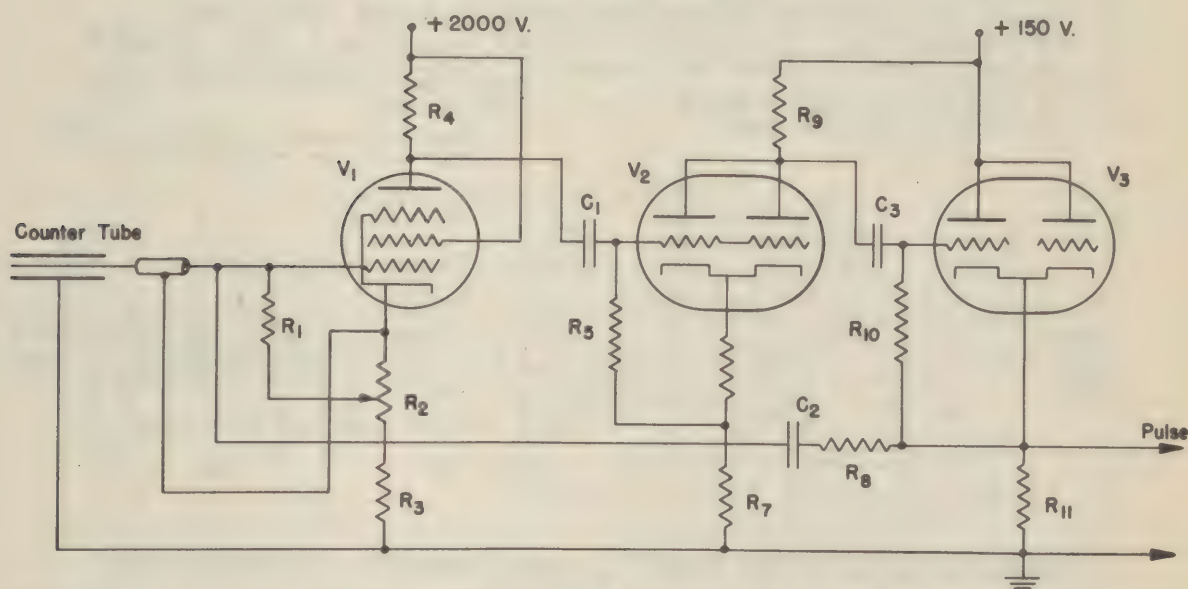
### NEHER-HARPER CIRCUIT

Neher, H.V., & Harper, W.W.,  
Phys. Rev., **42**, 940 (1936)

R<sub>1</sub>  $10^6 - 10^7$  ohms

R<sub>2</sub>  $\sim 10^6$  ohms

C  $\sim 10 \mu\text{f}$



### NEHER-PICKERING CIRCUIT FOR GROUND CATHODE COUNTING TUBES

R<sub>1</sub> 1 meg, 0.5 w.

R<sub>2</sub> 10 K

R<sub>3</sub> 1 meg, 1 w.

R<sub>4</sub> 240 K

R<sub>5</sub> 5 meg

R<sub>6</sub> 10 K

R<sub>7</sub> 20 K

R<sub>8</sub> 1.1 meg.

R<sub>9</sub> 56 K

R<sub>10</sub> 5 meg.

R<sub>11</sub> 20 K

C<sub>1</sub> 50  $\mu\text{f}$ , 3 KV

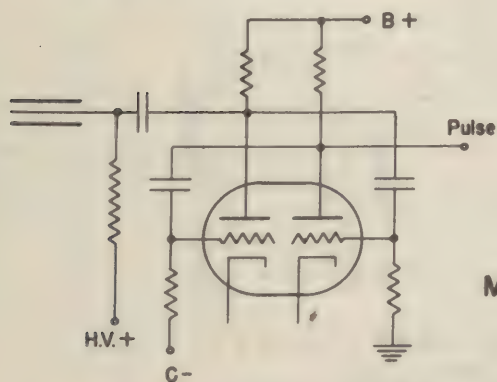
C<sub>2</sub> 250  $\mu\text{f}$

C<sub>3</sub> 100  $\mu\text{f}$

V<sub>1</sub> 6AK5

V<sub>2</sub> 6J6

V<sub>3</sub> 6J6

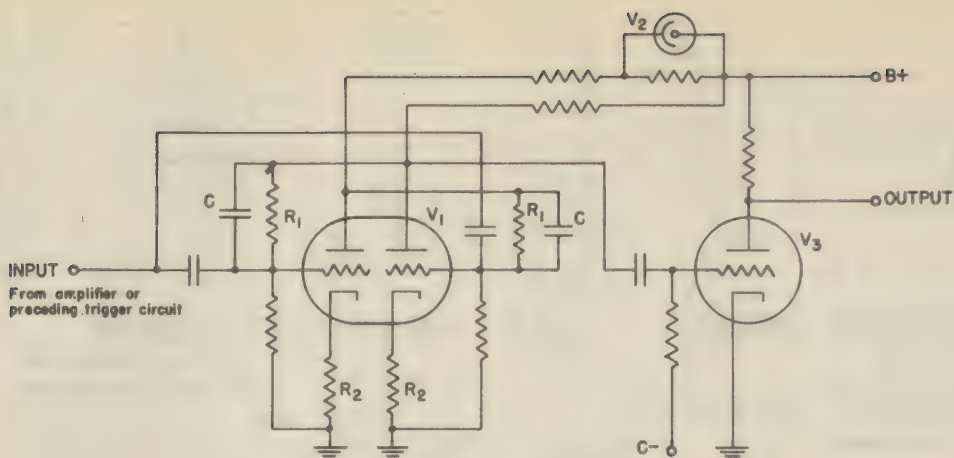


### MULTIVIBRATOR CIRCUIT

Gettling, J.A., Phys. Rev., **53**, 103 (1938)

Ruerk, A., Phys. Rev., **53**, 316 (1938)

Fig. 103 COUNTER QUENCHING CIRCUITS



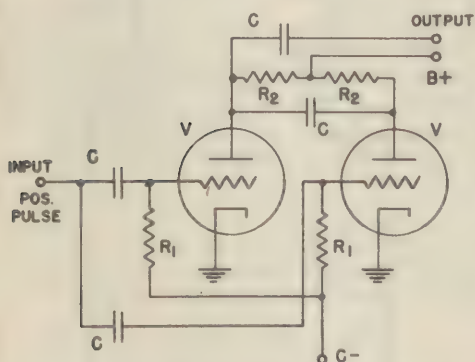
### SCALE-OF-TWO TRIGGER CIRCUIT

SCALES OF 4, 8, 16, 32, OR 64 ARE OBTAINED BY ADDING IDENTICAL UNITS IN SERIES.

$R_1$  ~ 400 K  
 $R_2$  40K OR MORE TO PROVIDE HIGH GRID BIAS.  
 $C$  ~ 40  $\mu$ f.  
 $V_1$  6N7, 6SL7 OR PAIRS OF SINGLE TRIODES.  
 $V_2$  NEON INTERPOLATING TUBE

$V_3$  6C5, USED AS A CLIPPER TO PREVENT PASSAGE OF NEGATIVE PULSES.  
 OTHER CIRCUIT CONSTANTS DEPEND ON THE TYPE OF TUBE.

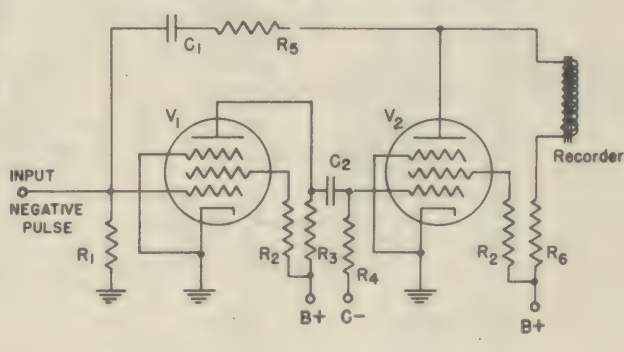
Lifschultz, H., & Lawson, J.L., Rev. Sci. Inst., 2, 83 (1938)  
 Eccles, W.H., & Jordan, Radio Rev., 1, 854 (1919)



### THYATRON SCALE-OF-TWO CIRCUIT

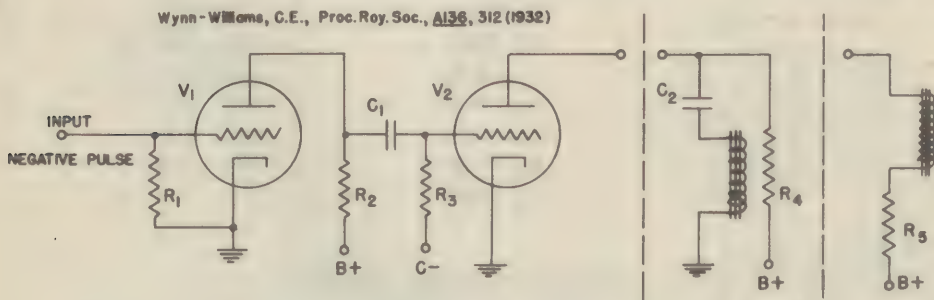
HIGHER SCALING FACTORS CAN BE OBTAINED WITH ADDITIONAL STAGES ARRANGED IN SERIES.

$R_1$  50 K  $C$  0.002  $\mu$ f.  
 $R_2$  20 K V THYATRON (e.g. 884)



### MULTIVIBRATOR RECORDING CIRCUIT

$R_1$  1 meg.  $R_6$  5 K.  
 $R_2$  50 K.  $C_1$  0.0001  $\mu$ f., 400 V.  
 $R_3$  0.1 meg.  $C_2$  0.001  $\mu$ f., 400 V.  
 $R_4$  0.5 meg.  $V_1$  6SJ7, 6C6  
 $R_5$  10 K.  $V_2$  Power amplifier, 6V6, 6F6, 6L6



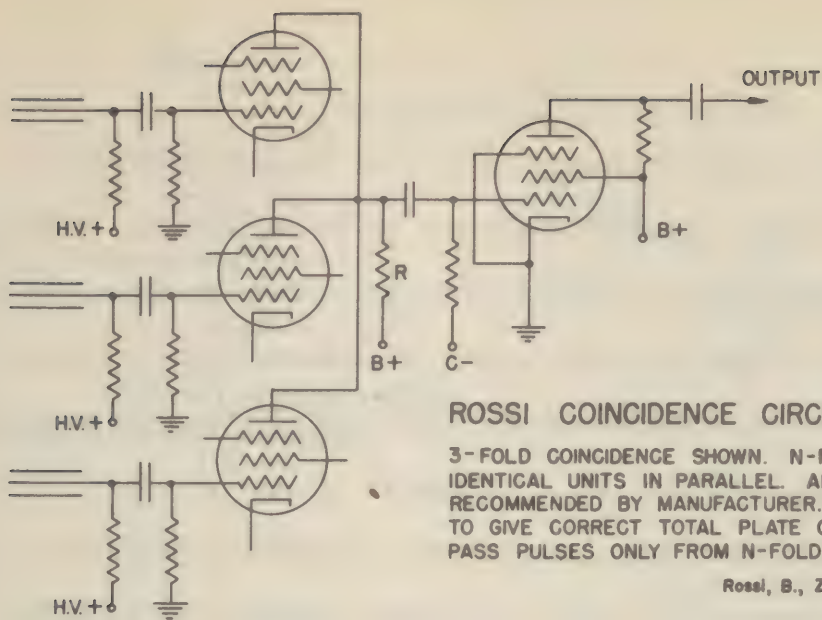
### THYATRON RECORDING CIRCUIT

TWO RECORDER ARRANGEMENTS ARE SHOWN BY BROKEN LINES.

$R_1$  0.5 meg.  $R_4$  0.2 meg.  $C_2$  1-4  $\mu$ f.  
 $R_2$  0.1 meg.  $R_5$  10 K.  $V_1$  TRIODE, 6C5  
 $R_3$  0.5 meg.  $C_1$  0.001  $\mu$ f.  $V_2$  THYATRON, 884

Fig. 104





### ROSSI COINCIDENCE CIRCUIT AND DISCRIMINATOR

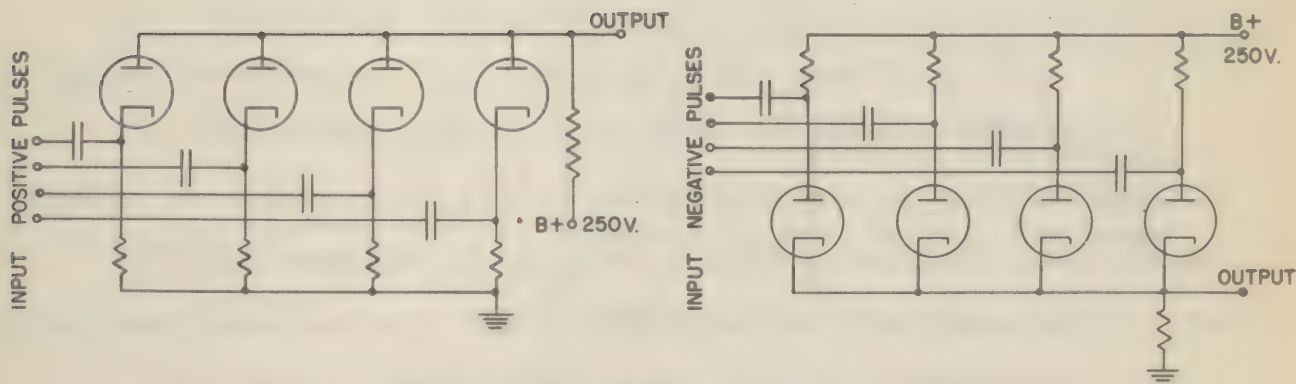
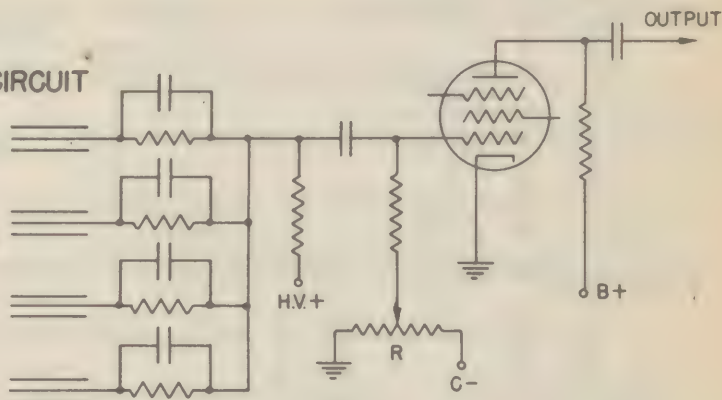
3-FOLD COINCIDENCE SHOWN. N-FOLD CIRCUIT CONTAINS N IDENTICAL UNITS IN PARALLEL. ALL CIRCUIT CONSTANTS AS RECOMMENDED BY MANUFACTURER. RESISTANCE R ADJUSTED TO GIVE CORRECT TOTAL PLATE CURRENT. C- ADJUSTED TO PASS PULSES ONLY FROM N-FOLD COINCIDENCES.

Rossi, B., Zeit. f. Physik, 59, 64 (1931)

### ADJUSTABLE N-FOLD COINCIDENCE CIRCUIT

ADJUSTMENT OF THE GRID BIAS VOLTAGE BY R DETERMINES THE MINIMUM NUMBER OF COUNTER DISCHARGES REQUIRED TO REGISTER A COINCIDENCE COUNT.

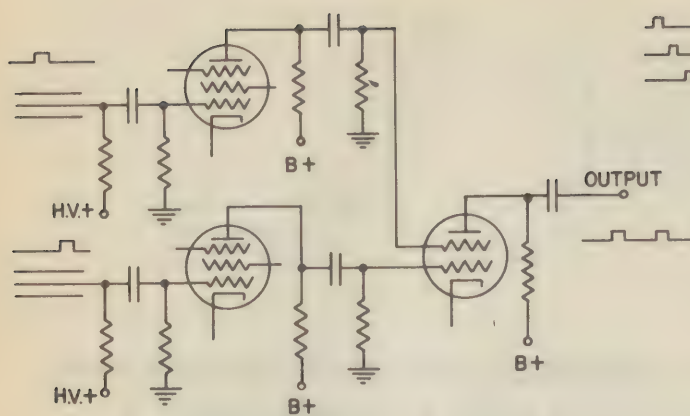
Ramsay, W.E., Phys. Rev., 57, 1061 (1940)



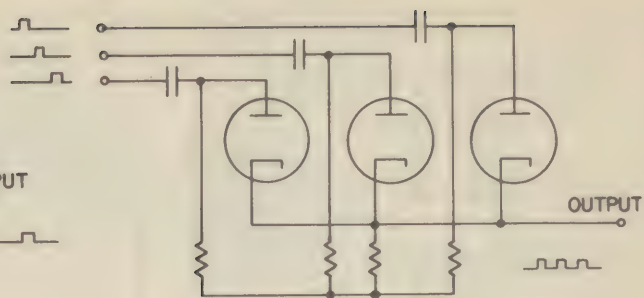
### DIODE COINCIDENCE CIRCUITS

Howland, et al., Rev. Sci. Inst., 19, 551 (1947)

Fig. 105

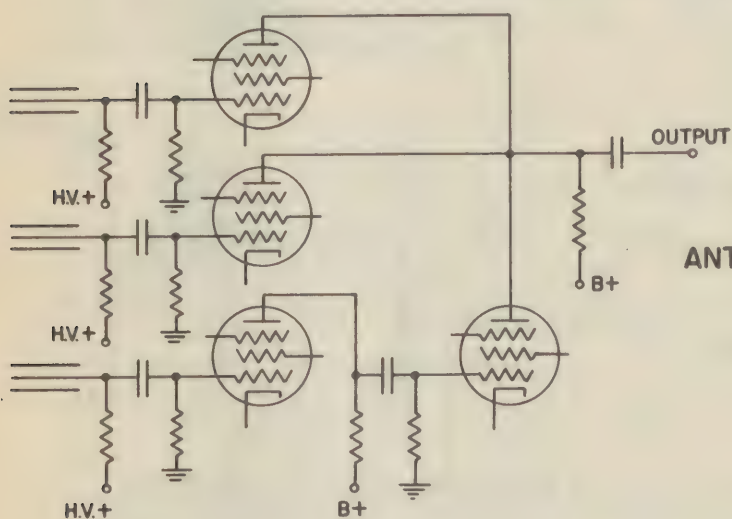


PULSE MIXING CIRCUIT



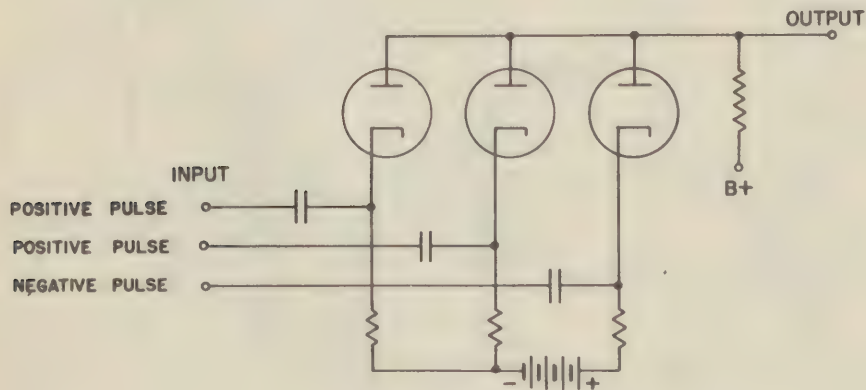
DIODE MIXING CIRCUIT

Howland, *et al.*, Rev. Sci. Inst., **18**, 551 (1947)



ANTI-COINCIDENCE CIRCUIT

Herzog, G., Rev. Sci. Inst., **11**, 84 (1940)



DIODE ANTI-COINCIDENCE CIRCUIT

Howland, B., Schroeder, C.A., & Shipman, J.D., Rev. Sci. Inst., **18**, 551 (1947)



## 19. PROPORTIONAL COUNTERS

### A. General Features and Use

The proportional counter is a variable gas-amplifying diode, and in general, similar to G. M. discharge tubes in construction and materials. The particular usefulness of this form of counter derives from the nearly linear relation between the pulse size provided by the counter and the total ionization produced initially in the counter by a charged particle. With appropriate electronic circuits, it is possible to discriminate between kinds of particles transversing the counter, and frequently, between similar heavy particles of different energies. Thus, in decreasing order of magnitude, definite pulse size for a particular counter can be associated with fission fragments, alpha particles, protons, electrons, and gamma photons. The property of discrimination can be used to advantage for reducing the observed background from light particles and gamma radiation when low intensities of heavily ionizing particles are measured, by adjusting the counting circuit to amplify and register only pulses larger than a predetermined size.

The design of proportional counters depends upon the radiation to be measured. For most applications, three forms are commonly used:

1. "Bell" shaped counters with tungsten wire anodes and with thin windows for detecting  $\beta$ , and  $\alpha$  radiations (see figure 100).
2. Cyclindrical glass or metal tubes with coaxial tungsten wire anodes (see figure 101) for  $\beta$ ,  $\gamma$ , n, radiations.
3. Point counters (1), similar to "bell" counters but with a spherical metal anode 1-2 mm in diameter supported near the counter window. The sensitive region of these counters lies only a small volume surrounding the ball anode. A fourth type developed by Zipprich, (2), consisting of two

parallel plate electrodes and an accelerating grid placed between the plates, is less often used but possesses the advantage of a well defined sensitive region.

Filling gases for proportional counters need not contain polyatomic or quenching gases although the inclusion of such gases provide greater stability, particularly for large pulses. The gases most frequently used are, a mixture of argon, 10-25%, and methane, 75-90%, and various mixtures of nitrogen, methane, ethane, and ether. Pressures commonly used vary from a few centimeters to half an atmosphere.

The operating voltage for a proportional counter is determined by plotting the counting rate against anode voltage. As shown in figure 99, the region for proportional pulse size lies between the starting voltage,  $V_1$ , at which the first counts are detected and the beginning of the transition to the Geiger-Müller region,  $V_2$ . For neutron counters, see Section J.

### B. Theory of Operation

When certain simplifying assumptions are made which appear to be valid for most proportion counters, the formation of a voltage pulse proportional to the initial number of ion pairs is adequately explained in terms of a Townsend avalanche (3, 4, 5). It is assumed that, a, the probability of electron photoemission is negligibly small.

b. probability for secondary electron emission by positive ions collected at the cathode is negligibly small.

c. negative ions ( $O^-$ ,  $F^-$ ,  $Cl^-$ , etc.) are not sufficiently numerous to produce an appreciable lag in the counter action.

d. recombination of positive ions and electrons within the gas is negligible.



From the,  $N$ , initial ion pairs produced by an incident charge particle, the electrons are collected at the anode in a time of the order of a few microseconds while the positive ions remain essentially stationary during this time. Within a distance of several mean free paths from the anode electrons acquire sufficient energy between collisions in the stronger field to produce additional ion pairs and, hence, a Townsend avalanche. The avalanche at this point differs from the Geiger-Muller counter discharge in that the descendants of a single electron multiply to a smaller and, on the average, a constant number which is a function of the operating voltage. The factor by which an electron multiplies itself in the avalanche, called the amplification,  $A$ , may have a value up to a maximum of  $10^4$  although generally is of the order of  $10^3$  or less. Within the range from 1 to  $10^4$ , its value can be chosen arbitrarily by the proper choice of operating voltage; a factor permitting some control over the pulse size which may be desired. When the amplification factor increases beyond  $10^{-3}$  or  $10^{-4}$ , due to a high operating voltage, the pulse size is no longer proportional due to the appearance of some of the characteristics associated with the Geiger-Muller discharge. Following the Townsend avalanche, the residual positive ion cloud drifts slowly to the cathode. However, during the dead time of roughly  $10^{-4}$  seconds, it still exists as a space charge sufficiently near the anode to reduce the effective electric field and thus prevent a second avalanche which might be initiated by a charged particle arriving within this time.

The total charge collected by the anode is approximately  $Q = eAN_0$  where  $e$  is the electron charge. With a total capacity of  $C$  for the counter and its immediately connected circuit, the peak pulse voltage is then

$$V = \frac{eAN_0}{C}$$

### References

1. Geiger and Klemperer, Zeits f. Physch. 36, 364 (1926)
2. Zipprich, B., Zeits f. Phys., 36, 364 (1926)
3. Rose, M.E. and Korff, S. A. Phys. Rev. 59, 850 (1941) ,
4. Loeb, L. B., Fundamental Processes of Electrical Discharge in Gases, Wiley (1939)
5. Korff, S. A., Electron and Nuclear Counters, Van Nostrand, (1946)



## 20. STANDARDIZATION OF RADIOACTIVE SAMPLES

### A. Introduction

The knowledge of the absolute intensity of radioactive samples is desirable for the uniformity and standardization of measurements and is highly important in dosage determinations. In this chapter, the most commonly used standardization methods for sources of alpha, beta, and gamma radiations will be described.

The methods and units of absolute standardization are not yet developed to an entirely satisfactory stage and the agreement between measurements made in different laboratories is not quite perfect. Efforts toward unification, however, have been undertaken by the National Research Council which recently established a committee on radioactivity to recommend standardization procedures and units in the United States.

### B. Units of Radioactivity

Conventionally, the unit of radioactive strength or quantity of a source is the curie. One curie corresponds to the quantity of the radioisotope which decays at the rate of  $3.7 \times 10^{10}$  disintegrations per second (one millicurie, 1 mc. =  $3.7 \times 10^7$  dis. per second; one microcurie, 1 uc. =  $3.7 \times 10$  dis. per sec.). Historically, the curie unit was originally used as a measure of the quantity of Radon gas ( $0.652 \text{ mm}^3$  at  $0^\circ \text{ C}$  and 760 mm Hg) in radioactive equilibrium with 1 gm of radium. Thus, the number of alpha particles emitted per second by 1 gm of Ra 226 is the same as for Rn 222 which, according to the most recent determination, is  $3.61 \times 10^{10} \pm 0.03$  per second per gm. Later, this definition of the curie was extended, first to quantities of other naturally radioactive decay products of radium beside radon, and

finally by general usage, to quantities of all radioactive isotopes. There is thus a discrepancy between the number of disintegrations of one curie of radon and the number of disintegrations adopted generally for one curie of any radioisotope.

It is not essential to use a unit of the magnitude of a curie to denote the quantity of a radioactive isotope since this quantity can often be expressed in terms of the absolute number of disintegrations per unit time for each sample. To avoid the ambiguities that arise in using the curie in two different senses, Curtis and Condon recently proposed a new unit, the Rutherford, which is the quantity of a radioisotope decaying at the rate of  $10^6$  disintegrations per second. This unit has certain merits in that it allows the use of the curie for the purpose originally designated; namely, to denote quantities of the radium decay products, and it is the most useful order of magnitude for tracer quantities. So far, however, the Rutherford unit has not found general acceptance.

In the following we shall make use of the curie (c, mc., and  $\mu$ c) unit in the sense defined at the beginning of this paragraph. In order to avoid ambiguity it should be mentioned that the rate of disintegration will be regarded as the number parent nuclei changing into daughter nuclei per unit time and not necessarily the number of particles emitted. In a radioactive isotope with a complex disintegration scheme where more than one particle or gamma ray is emitted, it is essential to know the decay scheme, the energies and percentages of each radiation. For example, in Na 24 (see: Decay Schemes) each emitted beta ray is followed very rapidly by 2 "coincident"  $\gamma$ -rays and though the rate of disintegration is the same as the rate of emission of beta rays,  $N_\beta = N_{\gamma_1} = N_{\gamma_2}$ , the total number of emitted rays per Na 24 disintegration is 3.



### C. General Methods

In most measurements, one is interested in the specific activity or the quantity of radioactive isotope per gram of sample substance expressed in curies per gm. If the entire quantity, i.e., every atom, of a particular element in the sample is radioactive, we speak of a carrier-free (CF) sample. The rate of disintegrations,  $R$  per sec., is related to the number of parent atoms,  $N$ ., and in a carrier-free isotope by:

$$R = \lambda N$$

where  $\lambda$  is the decay constant. It is, therefore, necessary to evaluate both  $\lambda$  and  $N$  to calculate  $R$ . This is possible in the preparation of standards by the suitable choice of the radioactive isotope. The number  $N$  can be determined either gravimetrically as is done in the preparation of some primary standards of uranium or it can be obtained by mass spectrographic deposition of a known amount of C.F. isotope. The second method has not been used so far for standardization purposes; however, it has been used for half-life determinations from which  $\lambda$  can be obtained.

### D. Primary Alpha Particle Standards

Simultaneous knowledge of the weight and disintegrations rate is possible for two of the long life natural alpha particle emitters: Uranium, and Radium 226. It is possible to take weighed amounts of these substances and count all alpha particles emitted from them in an alpha particle ionization chamber. Since the vast majority of alpha particles follow straight trajectories, have a well-defined range, and produce relatively large specific ionization, under certain conditions each particle crossing the sensitive volume of the chamber may be recorded, and corrections for absorption or

geometry can readily be made to determine the absolute number of particles emitted (1). By this technique, Kovarik and Adams (2) showed that 1 gm of uranium emits a total of  $2.501 \times 10^4$  alpha particles per second. Knowing the isotopic constitution of uranium, due to the work of A. O. Nier (3), the disintegration rate and half-life of each of its three isotopes can be determined as shown in Table I. The isotope best suited to alpha particle standards is UI.

Table 17

DISINTEGRATION RATE OF THE NATURALLY OCCURRING URANIUM ISOTOPES

Name	Mass	Abundance		Disint. per sec.	Half-life
UI	283	99.274	(5)	$1.223 \times 10^4$	$4.51 \times 10^9$ y (5)
AcU	235	0.71 g %	(5)	$0.055 \times 10^4$	$7.07 \times 10^8$ y (5)
UII	234	0.00518	(5)	$1.223 \times 10^4$	$2.35 \times 10^5$ y (5)
				$25.01 \times 10^4$ (2)	

Determinations of the number of disintegrations from 1 gm of radium, are in good agreement among early workers. One of the best methods used for determining the quantity of radium is to measure the radon in radioactive equilibrium with it. The International Radium Standard Commission (4) recommended the value  $3.7 \times 10^{10}$  disintegrations per gm of Ra per sec. This is an average of the result of several investigators. Recently, however, Kohlman obtained a new value of  $3.61 \times 10^{10} \text{ g}^{-1} \text{ sec}^{-1}$ . Some methods of beta and gamma ray standardization go back to the well established alpha particle standard. Both the new values for radium and for UI given are believed to be correct to about 1%.



### E. Beta Particle Standards

This presents, technically, a more difficult problem than that of alpha particle standardization due mainly to scattering effects and absorption characteristics of beta particles. One seeks easy standardization methods for beta particles with energies ranging from 0.015 mev to 3 mev corresponding to the range encountered with most radioisotopes.

Even though it has been established that better than 99 per cent of all beta particles that reach the sensitive volume of good counters give rise to a pulse and may be counted, certain precautions are necessary in determining the fraction of the total particles from the sample which do reach the sensitive volume. This involves mainly geometrical efficiency and absorption corrections.

Several independent methods are available for preparing beta samples of standard intensity which, together with procedures for comparing one beta emitter to another, are described below.

### F. The Uranium Standard

When the beta emitters, UI, UX<sub>1</sub>, UX<sub>2</sub>, UZ have reached radiative equilibrium (see figure 107), then

$$N_1 \lambda_1 = N_2 \lambda_2 = N_3 \lambda_3 = N_4 \lambda_4 = 1.223 \times 10^4 \text{ disint. per sec. per gm U.}$$

$N_1$ ,  $N_2$ ,  $N_3$ ,  $N_4$ , and  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ , are the number of atoms and the disintegration constants respectively of UI, UX<sub>1</sub>, UX<sub>2</sub>, and UZ.

The level scheme of the beta and gamma radiations is not entirely satisfactorily explored as yet, but a recent one proposed by Bradt and Scherrer (6) is shown in Figure 107. The beta radiations of UX<sub>2</sub> represent 99.85 per cent of all disintegrations of UX<sub>2</sub>, the rest, 0.15 per cent, being gamma ray that produces

UZ. Further, 98 per cent of  $UX_2$  beta particles are of 2.32 mev maximum energy, while 2 per cent consists of one or more beta particles of 1.5 mev in coincidence with the gamma rays. If a known amount of uranium is deposited on a foil and allowed to equilibrate with  $UX_1$  and  $UX_2$ , a combined  $\alpha$ - $\beta$  standard source can be obtained. The alpha particles of UI and UII and the beta particles of UX have to be absorbed if the  $UX_2$  beta emission is to be used for standardization purposes. This is readily done with 25 mg. per  $cm^2$  aluminum foil which absorbs all alpha and  $UX_1$  particles but only about 5% of the  $UX_2$  beta particles.

A convenient method for making a uniform deposit of uranium on a foil is to prepare a colloidal suspension of  $U_3O_8$ . Pure  $U_3O_8$  mixed in water is ground in a stainless steel quartz ball mill for twelve hours and the water then allowed to evaporate. The material is taken up by suspending agent such as chloroform or ethyl alcohol and centrifuged to precipitate the coarse particles. The remaining colloidal suspension is then evaporated in a standard holder by the radiant heat from a general electric heat lamp. The amount of material deposited is determined by weighing the aluminum foil before and after deposition.

#### G. RaD and RaE Standards

In aged rocks with uranium content, the radium and its decay products are in equilibrium and the radium content of these rocks may be determined, for example, from the Ra Em producing power. Knowing the radium content, the quantity of RaD can also be calculated and, along with other lead isotopes, separated quantitatively from the rock sample. Given time, equilibrium will be reached between the RaD and its daughter substance RaE. The radiations emitted by this sample are then as follows:



Table 18 . RADIATIONS FROM RaD, RaE, Po

Element	$\alpha$ mev	$\beta$ mev	$\gamma$ mev	T
RaD 210	-	0.025	0.047	22 years
RaE 210	-	1.17	-	5.0 days
Po 210	5.298	-	-	140 days

The number of disintegrations from RaD and RaE being known, one may use such a sample for  $\beta$ -ray standardization by absorbing the radiations of RaD, and Po 210. This may be done with an Al absorber of 10 mg per  $\text{cm}^2$ . Samples of this type have been recently prepared with the M. I. T. group and by the Bureau of Standards\*. On comparing a Uranium and a RaD + RaE beta particle standard by means of G. M. counters, corrections have to be made for the differences in absorption in the counter wall and in scattering of the 1.17 mev and 2.32 mev beta particles. Similarly these corrections will have to be made with all other beta emitters. Before describing such corrections, a third independent method is presented for preparation of beta particle standards. This method also determines the beta and gamma ray efficiencies of Geiger-Mueller counters.

#### H. The Coincidence Method

Rossi was the first to use the coincidence counting method. By means of his electronic circuit it is possible to record the simultaneous occurrence of pulses generated in G. M. counters with a resolution of  $10^{-7}$  seconds. The beta particles in a number of radioactive substances are followed within a

\* The Tracerlab, Inc., Boston, makes standard samples commercially.

short time interval by one or more gamma rays. It has been shown that in some radioactive substances the direction of the beta particle and of the gamma rays in coincidence are independent of each other, and it is assumed that this is also true for all  $\beta$ - $\gamma$  emitters. Coincidence counting may be used as an aid to study level schemes. In radioactive isotopes where the level scheme is known one may use the coincidence method with  $\beta$ - $\gamma$  coincidences to determine either the absolute number of disintegrations or the efficiency of beta and gamma counters. Both the unknown disintegration rate,  $N$ , and the efficiencies  $e_\beta$  and  $e_\gamma$  of the beta and gamma counters can be determined from the expressions given below.

$$\begin{array}{ll} Ne_\beta = B & e_\beta = \frac{G}{C} \\ Ne_\gamma = G & e_\gamma = \frac{B}{C} \\ Ne_\beta e_\gamma = C & N = \frac{C^2}{BG} \end{array}$$

$B$  = corrected  $\beta$  particle counting rate.

$G$  = corrected gamma counting rate.

$C$  = corrected coincidence counting rate.

This method has already found application in the preparation of beta standards by the use of Co 60 which may be prepared and effectively standardized as a primary standard by the coincidence procedure. This isotope has advantages as a standard because of its relatively long life (5.3 years), its low energy ( $E_{\max} = 0.3$  mev), simple beta spectrum, its permanency in preparations, (e.g., it may be electroplated on standard sample discs), and the additional fact that, due to its two gamma rays, it may also be used for primary gamma radiation standard.



## I. Gamma Ray Standards

Gamma ray standards may be used for standardization of gamma ray and also for beta particle disintegration rates if the beta-gamma level scheme is entirely known. Primary standards usually are made of radium in equilibrium with its decay products and more recently of Co 60, the same isotope used for beta particle standards. The ionization measured in a standard dose meter from these sources is

$$1 \text{ curie Ra} = 0.84 \pm 0.02 \text{ rhm (0.5 mm Pt shield)}$$

$$1 \text{ curie Co}^{60} = 1.30 \text{ rhm}$$

The following table gives the ionization in air as a function of the gamma ray energy and the distance from the source for various gamma ray energies (7).

Table 19. IONIZATION BY GAMMA SOURCES OF DIFFERENT ENERGY

$\gamma$ energy mev	Ionization mrh		
	1 cm	1 foot	5 feet
0.5	2,900	3.1	.1
0.8	4,600	2.8	.2
1.0	5,600	6.0	.2.5
1.5	7,600	8.1	.3
1.8	7,800	8.3	.3.1
2.0	9,300	9.9	.4.1
2.5	10,400	11.1	.43
3.0	11,700	12.5	.48
4.0	14,000	14.0	.58

Many known isotopes have more than one gamma ray so that the following table, made up from data furnished by Sullivan (8) is also useful for determination of gamma ray intensity.

Table 20. SOURCE STRENGTH OF VARIOUS ISOTOPES

Isotope l mc		$\gamma$ mev	m r h/m
Na	22	1.3	1.30
Na	24	1.38 2.76	1.92
Mn	52	1.0	1.93
Mn	54	0.85	0.485
Fe	59	1.1 1.3	0.651
Co	58	0.83	0.560
Co	60	1.0 1.3	1.50
Zn	65	0.51 0.45 1.14	0.30
Br	82	0.55 0.79 1.35	1.50
I	128	0.4	0.018
I	130	0.6 0.74	1.25
I	131	0.08 0.37	0.26

In measurements of sample intensity by means of gamma ray ionization, one should exercise great care in keeping a standard geometry (distance of samples to ion chamber, amount of absorber and scatterer present). The quality of gamma rays changes appreciably by absorption or scattering (see: Gamma Rays) and the ratio of gamma ionization of two different energy gamma rays



changes correspondingly.

### J. Geometrical Efficiency

Much of the beta particle standardization work is carried out using bell-jar type Geiger Muller counters with thin mica windows. For these, and also for other kinds of counters, appropriate calculations may be carried out expressing their counting efficiency so far as solid angle is concerned. Diagram 108 shows a convenient arrangement to determine the efficiency of such counters. The counter is assumed to have a "sensitive volume" that may be approximated by the cylindrical volume limited by the counter wall and which begins at a usually unknown distance "b" (see diagram) behind the window. If the filling gas has proper characteristics, each particle gives rise to a discharge and is counted provided one portion of its path goes through the sensitive volume. The fraction of the total number of beta particles that go through the sensitive volume from a point source placed at a known distance from the counter window along the centerline of the counter may be determined by a simple formula, provided one neglects the absorption of the particles in the counter window and airspace, and the scattering from the sample support:

$$\Phi = 0.5 (1 - \cos \alpha)$$

$\Phi$  is often called the geometrical efficiency

$$\tan \alpha = \frac{r}{a + b}$$

Here b is still not known and one simple way to determine it is to measure a sample with a known disintegration rate and relatively high energy beta rays (P 32 or UX 2 is suitable) on several shelves. In counters with 1" - 1-1/2" wall diameter the distance of the sensitive volume from the window is usually .4 to .8 cm.

In order to compare the counting rates of a radioactive point source of negligible thickness placed at different distances from the window, or of two different isotopes, two corrections have to be made: a, absorption correction for the rays absorbed in the counter window and the air between the sample and window; b, back scattering correction for the increase in the counting rate due to the sample support. These corrections have to be applied after the customary adjustment in the counting rate is made due to: c, missed counts during the insensitive periods of the counter; d, background; e, subtraction of the counting rate of gamma rays, if any, are emitted from the source.

A customary way to account for absorption in the counter window is to measure the counting rate with no absorber, than with mica or Al absorbers of varying thicknesses placed between the sample and counter window. For good results, the absorbers should be quite close to the counter window. The absorption curve thus obtained may be extrapolated, knowing the window-thickness, to "zero absorber". This method is also satisfactory for correcting the air absorption if the sample is placed quite close to the window.

In measuring the absorption of beta particles from a point source with a Geiger-Muller counter, one should bear in mind that, due to the isotropic distribution of the beta particles in all directions of space, most of them will cross the absorber and the counter window at oblique angles. The effective thickness of the absorbers thus will not be  $t$ , the measured thickness, but a somewhat greater value when the "obliquity" correction is applied. The effective thickness is given by

$$t_{\text{eff}} = \frac{-t \ln \cos \alpha}{1 - \cos \alpha} = \frac{-t \ln \cos \alpha}{2 \Phi} = t \psi$$

$\psi$  = obliquity factor.



The following table gives an idea of the magnitude of the geometrical efficiency  $\Phi$  and the obliquity factor  $\Psi$  as a function of the angle  $\alpha$ .

Table 21

GEOMETRICAL EFFICIENCY AND OBLIQUITY FACTOR FOR  
A POINT BETA RAY SOURCE

$\alpha$	$\tan \alpha = \frac{r}{a+b}$	Geometrical efficiency $\Phi$	Obliquity factor $\Psi$
80°	5.671	0.468	2.10
60°	1.732	0.250	1.39
40°	0.839	0.117	1.18
30°	0.577	0.067	1.07
20°	0.364	0.0302	1.03
10°	0.176	0.0076	1.01
5°	0.0875	0.00195	1.00

If there is more air interposed between sample and counter, a satisfactory way to account for absorption and scattering by the air is to evacuate the space between sample and counter window. The absorption method indicated above may lead to as much as 10% error. On the whole, absorption corrections should be trusted only if the resulting correction is smaller than 30% of the counting rate. Typical absorption curves for three commonly used isotopes are given in diagram 109.

Backscattering correction may be obtained by piling foils of various thickness under the sample and observing the rise in counting rate. Beyond a certain thickness the backscattering remains essentially constant. Aluminum backscattering curves are given in diagram 110. These are not absolute since the absolute amount of backscattering is difficult to obtain with a Geiger-

Müller counter because the angular distribution of the scattered rays is not isotropic. The saturation backscattering varies greatly with the atomic number and diagram lll shows this variation. It is also possible to plot curves for saturation backscattering as a function of maximum energy of the beta rays for various backscattering materials. Above  $E_{\text{max}} = 0.6$  mev saturation backscattering, especially for light elements, is quite constant. For this reason some laboratories mount their standards on thick sample supports.

#### K. Extended Thin Samples.

The geometrical efficiency of a point source decreases if the point source moves out from the axis of the bell jar counter in a plane perpendicular to the axis. It is possible to write theoretical formulas for the change\*. In practice, however, it is easier to approach this subject experimentally and obtain experimental efficiency curves, especially since the obliquity factor changes too. Some of these are reproduced in daigram lll. By approximating the decrease efficiency curves plotted in the diagram with parabolas, it is seen that a disc of the same diameter as the counter would be less efficient than a point source of the same strength. The following table gives an idea of the efficiencies obtained after integration over the entire sample area.

Table. 22 . RELATIVE EFFICIENCY OF DISC TO POINT SOURCE

P 32	Geometrical efficiency of point source at center	Radius of disc = r	At center radius = r/2
Shelf 1	0.175	0.75	0.95
Shelf 2	0.0505	0.87	0.975
Shelf 3	0.0245	0.93	0.99

\*For example H. Weltin worked out such formulas (University of California at Santa Barbara).



In biological work it is often desirable to use sample dishes of a somewhat extended surface. The above figures indicate that the radius of those dishes should be not much larger than one-half the counter diameter if accuracy is desired. Caution should be used in applying sample deposition processes e.g., electroplating, if the distribution of the radioactive substance is not uniform over the surface of the sample. In particular, if more of the radioactivity is concentrated on the edges, the above cited efficiency figures are not valid. Variable distribution on the sample dishes will lead to variable counting rates from equally strong samples. The data given for P 32 above should be modified for calculating counting efficiency of low energy beta ray samples, mainly due to the effect of oblique absorption.

It is possible to construct supporting surfaces for radioactive samples which have equal geometric efficiency over their entire surface, thus permitting somewhat unequal distribution of the thin samples. In practice this may be achieved by using watch glasses of proper diameter.

#### L. Thick Samples

In biological work it is often necessary to deposit material of considerable thickness on the sample plates. Some of the beta particles emitted will be then absorbed or scattered by the sample itself. To correct for "self-absorption", a correction curve is obtained by measuring the counting rates obtained from different weighed amounts of the radioactive sample deposited on standard sample discs and comparing it with the counting rate expected without self absorption (9). One may then measure the counting rate of the unknown sample; determine its thickness by weighing and from the correction curve correct the counting rate for self absorption. The following table gives the fractions of C 14 beta particles counted from various self-absorption thicknesses.

Table 23 .

RELATIVE COUNTING EFFICIENCY AS  
A FUNCTION OF SELF-ABSORBER THICKNESSC 14 ( $E_{\max}$  151 mev)BaCO<sub>3</sub> self-absorber

Sample Thickness	Efficiency
0	1.0
1.5	0.80
3	0.63
6	0.43
9	0.31
12	0.24
15	0.19
18	0.16
21	0.14

M. Comparison Between Different Standards

No publications exist so far dealing with the comparison between different methods of standardization. The authors have recently compared standards on a bell jar counter using the coincidence method, a standar uranium preparation, and an RaE beta standard prepared by L. F. Curtis of the Bureau of Standards. Using the corrections described above, fairly good agreement was found between the respective standards. The numerical data are given in table 24.



Table 24 . SAMPLE OF COMPARISON OF DIFFERENT STANDARDIZATION METHODS

Isotope	$\beta$ energy mev	$\gamma$ energy mev	Net (measured efficiency)	Correction factor (ab- sorption, reflection, etc.)	Corrected Efficiency
Co 60	0.3	1.0 and 1.2	0.0148	.525	0.0235
I 131	0.6	0.4 and 0.08	0.0193	.746	0.0236
Na 24	1.48	1.36 , 2.76	0.0220	.96	0.0230
Au 198	0.78	0.46	0.0209	0.92	0.0230
RaD and E			0.0358	1.46	0.0245
Geometrical efficiency	-----				0.0242
Average	-----				0.0236

From the data given above it is possible to plot an efficiency curve for the mica window G.M. counter as a function of the beta particle energy. Such a curve is plotted in diagram 112. A similar curve may be constructed for gamma ray counting efficiency.

In conclusion one may suggest that for those not having a coincidence counting arrangement the use of a standard beta ray sample is desirable. UI, RaD and E, or Co 60 are about equally well suited for such a standard.

#### References

1. Geiger and Rutherford, Phil. Mag. 20, 691 (1910).
2. Kovarick, A. F., Adams, T., J. App. Phys. 12, 296 (1941); Phys. Rev. 40, 718, (1932); Phys. Rev. 54, 413 (1938).

3. Nier, A. O., Phys. Rev. 55, 150 (1939)
4. Curie, M. Debierne, A., Eve, A. S., Geiger, H., Hahn, O., Lind, S. C.,  
Meyer, St., Rutherford, E., Schweidler, E., Rev. Mod. Phys. 3, 427 (1931).
5. Seaborg, G. T., Rev. Mod. Phys. 16, 1 (1944).
6. Brandt, H., and Scherrer, P., Helv. Phys. Acta 18, 425 (1945).
7. Evans, R. D., Radioactivity Units and Standards, Committee on Radio-  
activity, National Research Council.
8. Sullivan, W. H., Chem. Eng. News, An. Ed. 25, 1862 (1947).
9. Yankwich, P. E., Norris, T. H., and Huxton, J. Analyt. Chem. 19, 429 (1947).



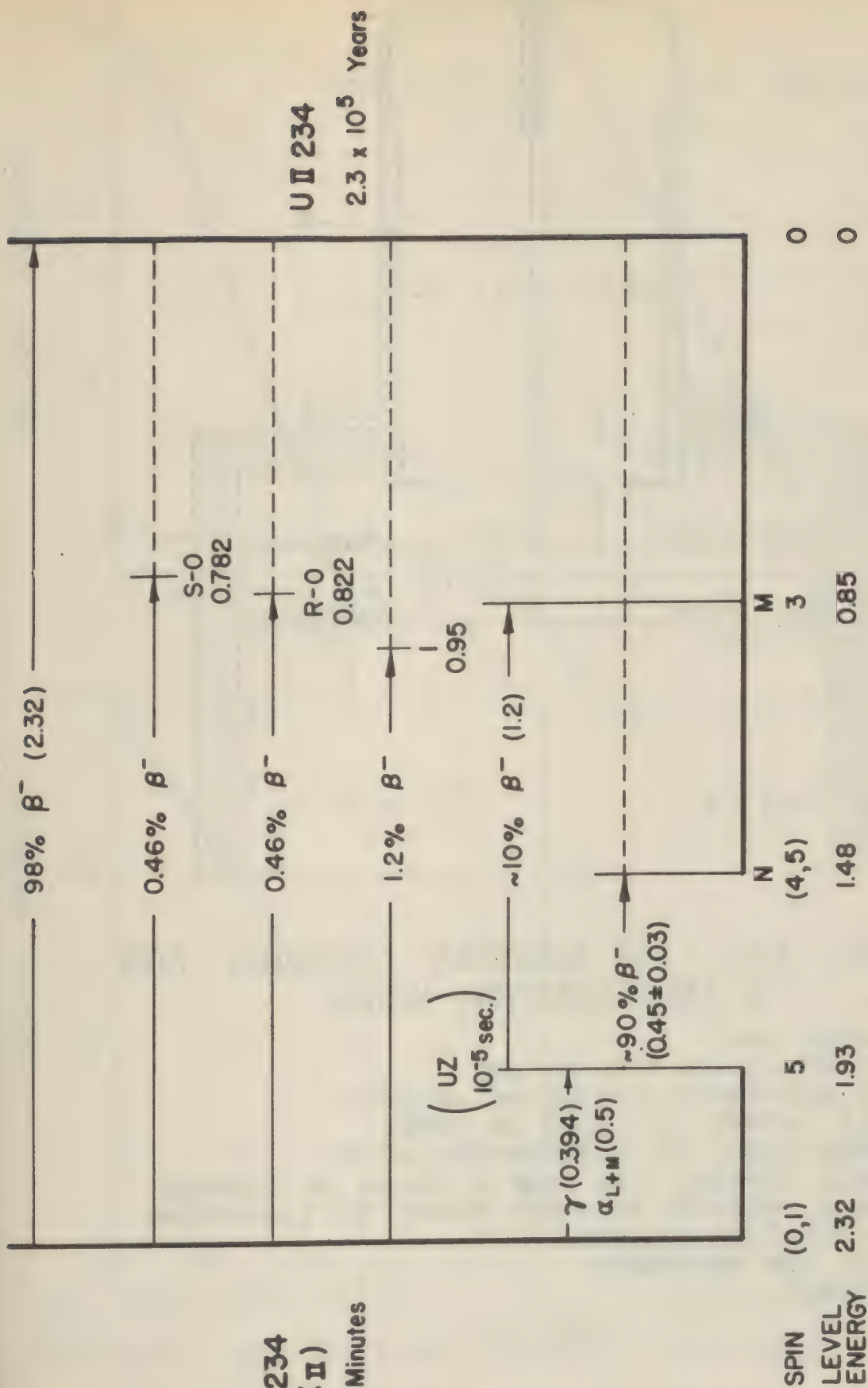
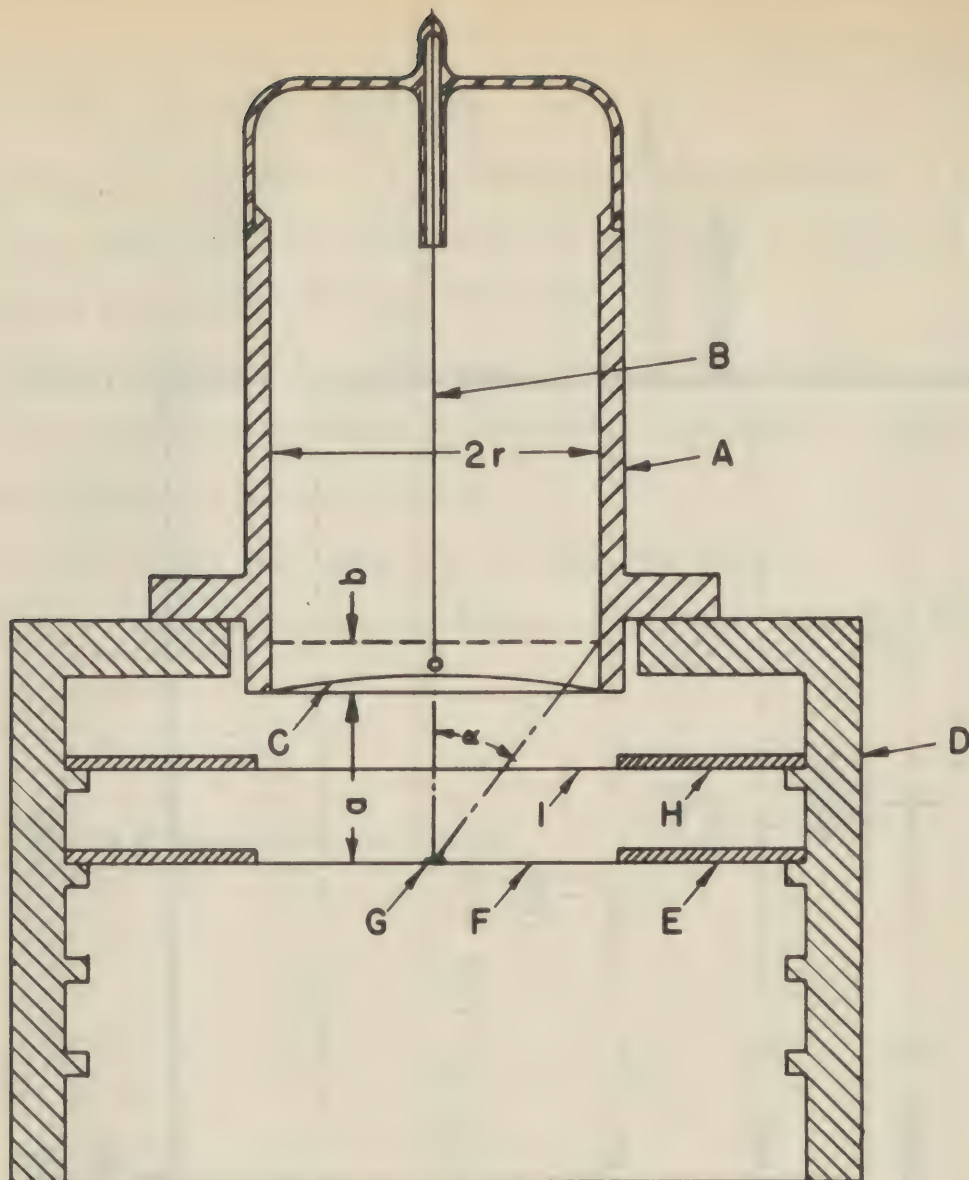


Fig. 107

DECAY SCHEME FOR  $UX_{II} \rightarrow U_{II}$ 

ALL ENERGIES ARE IN UNITS OF MEV. LEVEL ENERGIES ARE GIVEN WITH RESPECT TO THE 2.32  $\beta^-$  TRANSITION.

Bradt, H., & Scherrer, P., *Helv. Phys. Acta.*, **18**, 425 (1945)



## TYPICAL BELL-JAR COUNTER ASSEMBLY FOR STANDARDIZATION WORK

- A. COUNTER WALL
- B. WIRE WITH GLASS BEAD ON END
- C. THIN MICA WINDOW (1-2 mg./cm.<sup>2</sup> preferable)
- D. SHELF SUPPORT OF LUCITE OR PAPER
- E. SAMPLE SHELF OF ALUMINUM OR LUCITE
- F. SAMPLE SUPPORT, THIN FILM OF NYLON OR ALUMINUM
- G. SAMPLE, PREPARED AS POINT SOURCE BY EVAPORATING  
0.1-0.2 cm.<sup>3</sup> OF SOLUTION
- H. SHELF FOR ABSORBERS
- I. ABSORBER

Fig. 108



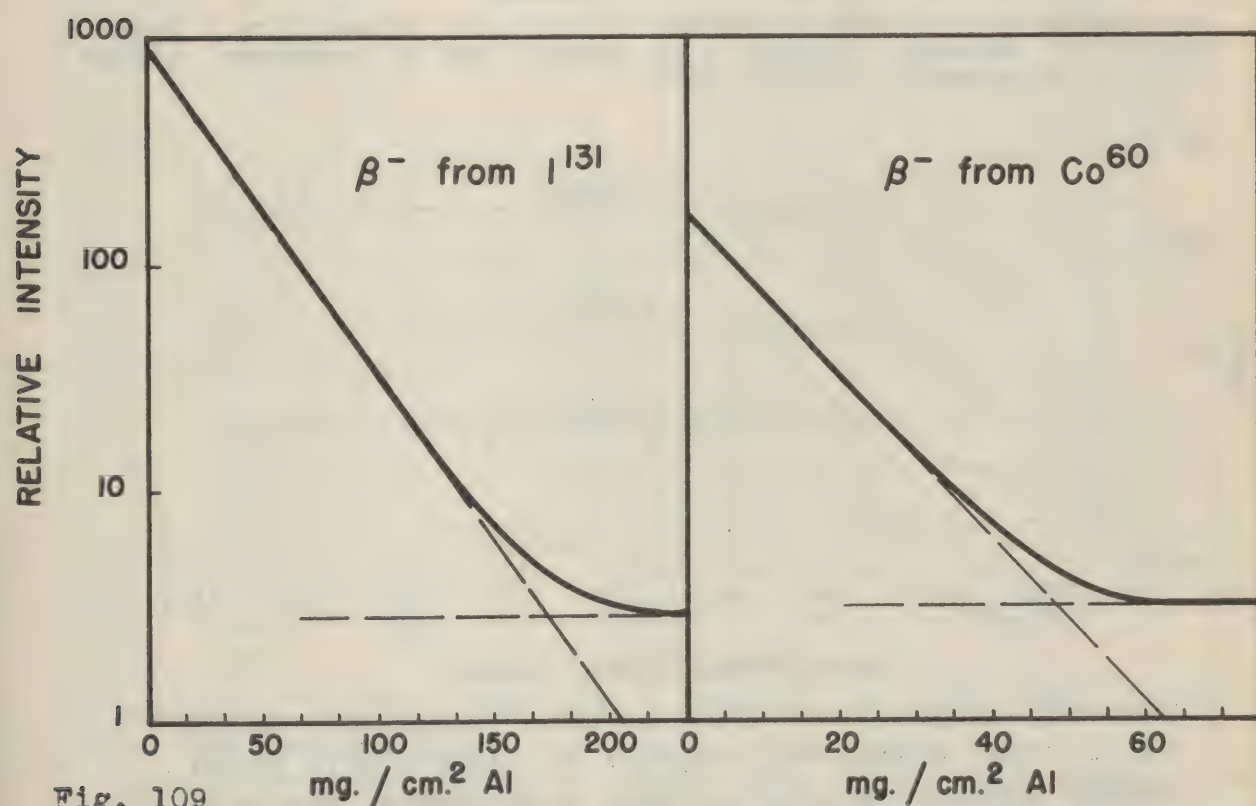
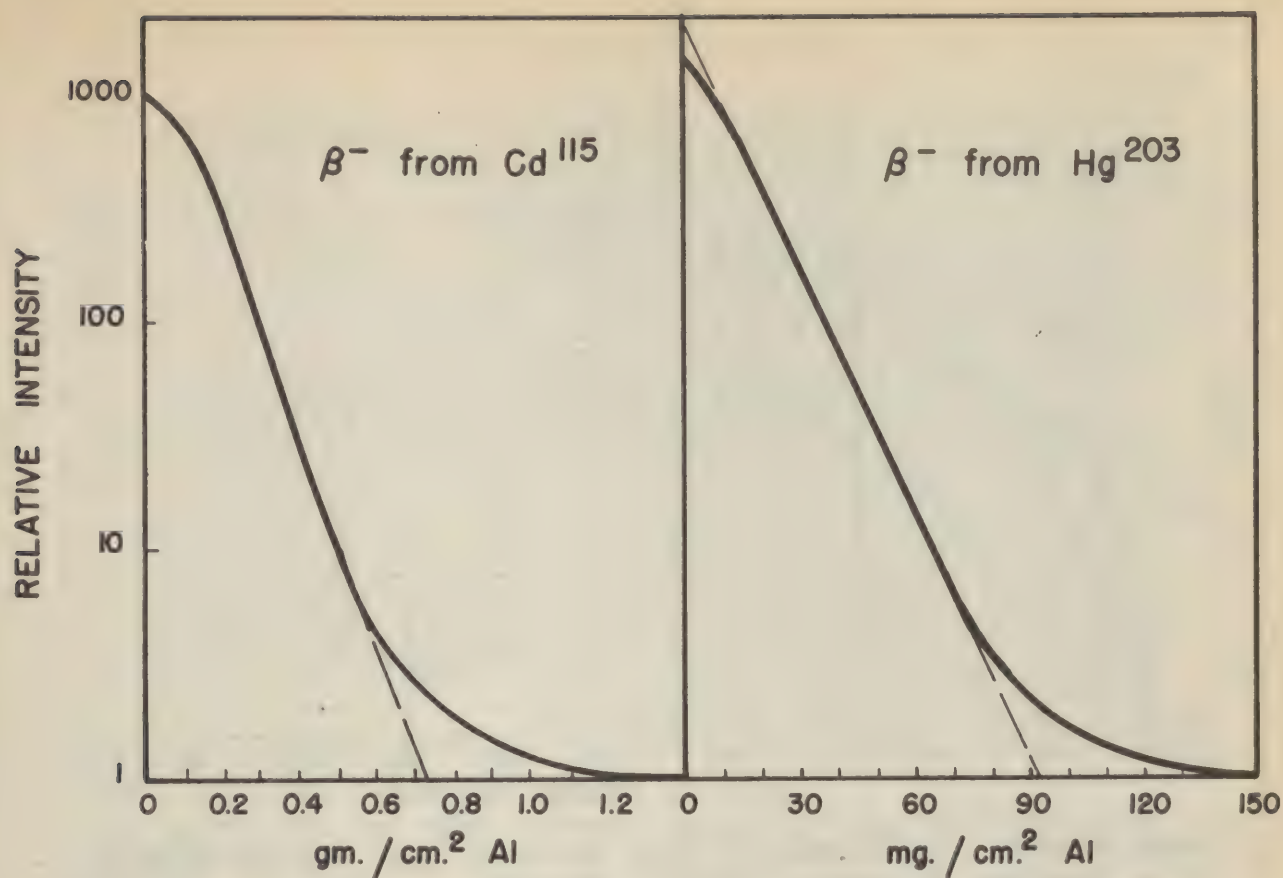
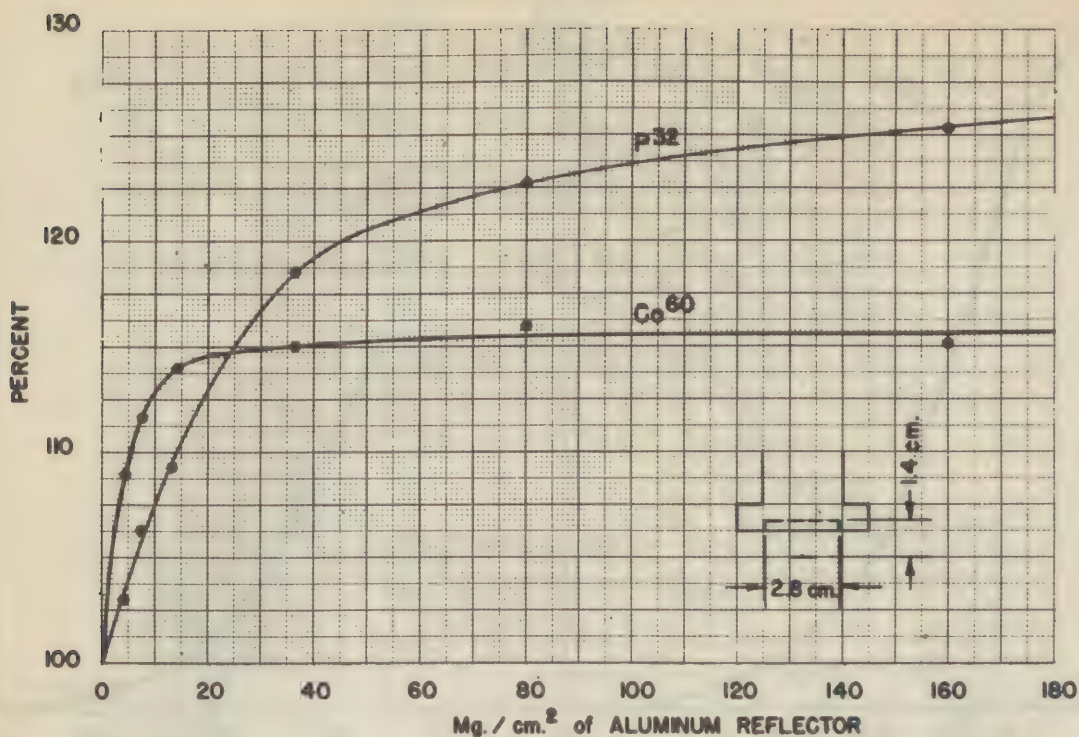


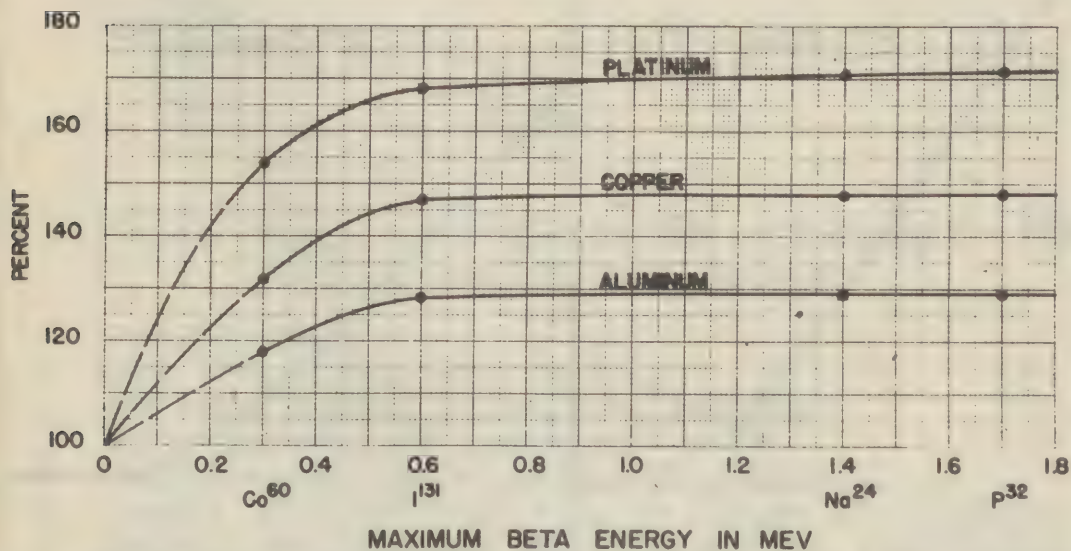
Fig. 109

TYPICAL ABSORPTION CURVES FOR BETA PARTICLES



BACKSCATTERING OF P<sup>32</sup> AND Co<sup>60</sup> BETA PARTICLES ( $E_{\max.} = 1.72$  and 0.3 MEV) AS A FUNCTION OF SAMPLE SUPPORT THICKNESS.

THE COUNTING RATE IS GIVEN IN PERCENT OF THE RATE OBTAINED WITH A SAMPLE SUPPORT OF NEGLIGIBLE THICKNESS. THE SAMPLES MAY BE CONSIDERED AS POINT SOURCES, THE GEOMETRY IS SHOWN ABOVE.

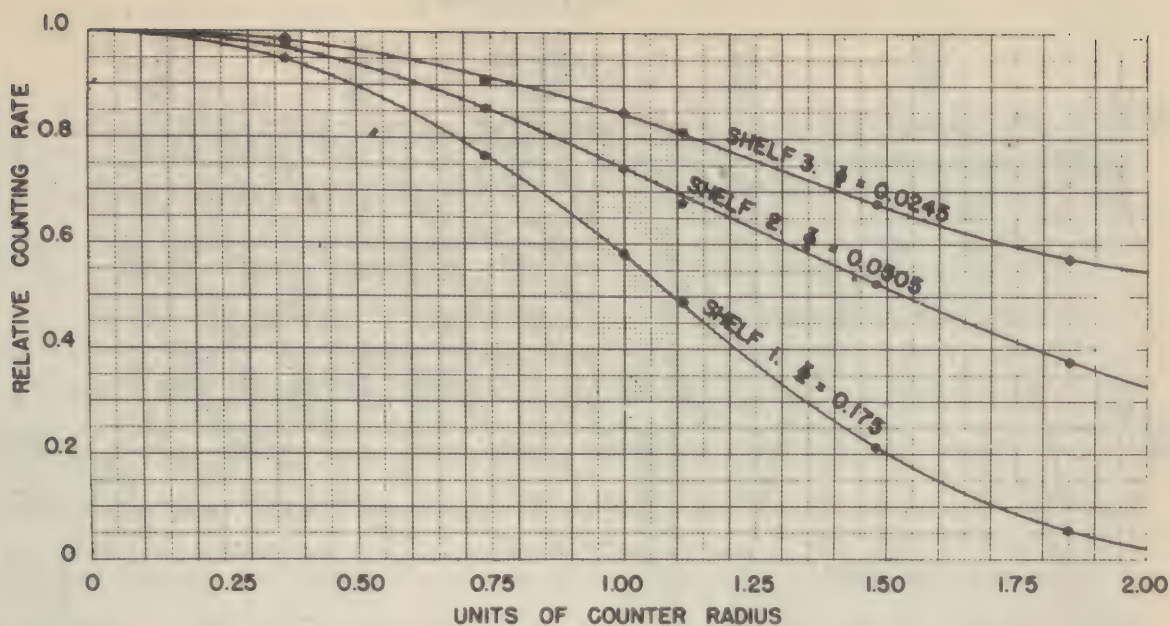


SATURATION BACKSCATTERING FROM ALUMINUM, COPPER, AND PLATINUM FOR A POINT SOURCE AS A FUNCTION OF MAXIMUM BETA ENERGY.

ORDINATE REPRESENTS COUNTING RATE WITH RESPECT TO A SOURCE WITH NO BACKSCATTER (NEGLIGIBLY THICK SUPPORT).

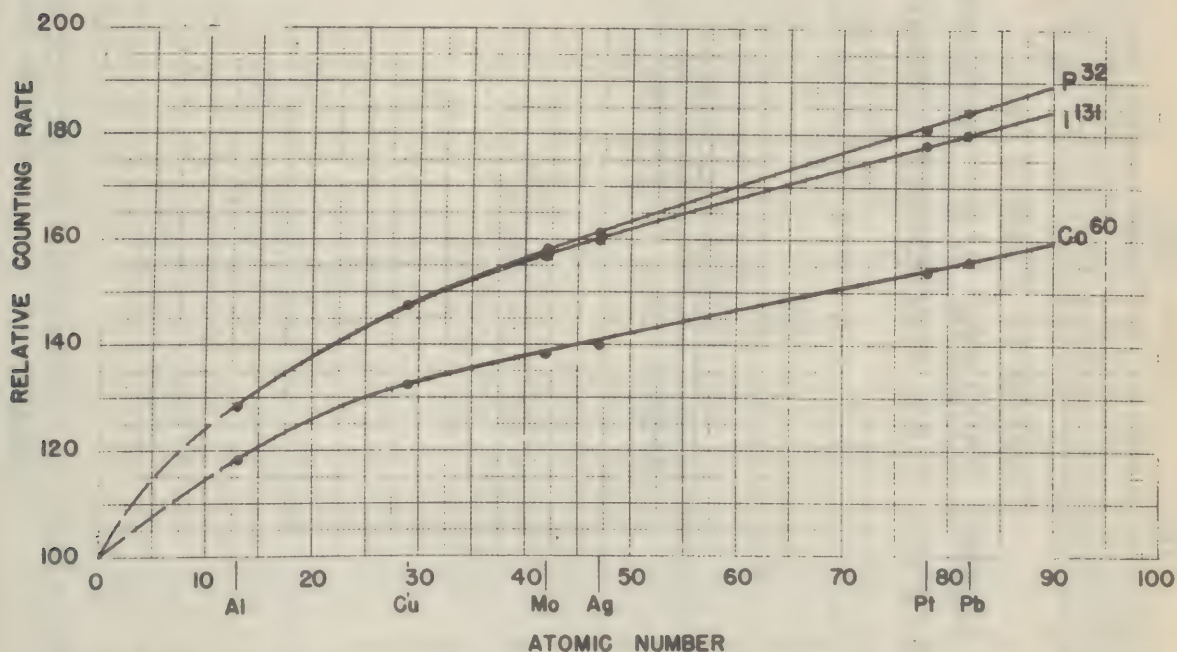
Fig. 110





RELATIVE COUNTING EFFICIENCY (OF  $P^{32}$ ) AS A FUNCTION OF THE DISTANCE FROM THE AXIS OF THE COUNTER.

DATA WERE TAKEN ON THREE DIFFERENT SHELVES OF THE COUNTING SYSTEM SHOWN ON DIAGRAM. ON EACH CURVE THE COUNTING RATE OBTAINED AT THE AXIS IS REGARDED AS 100%.

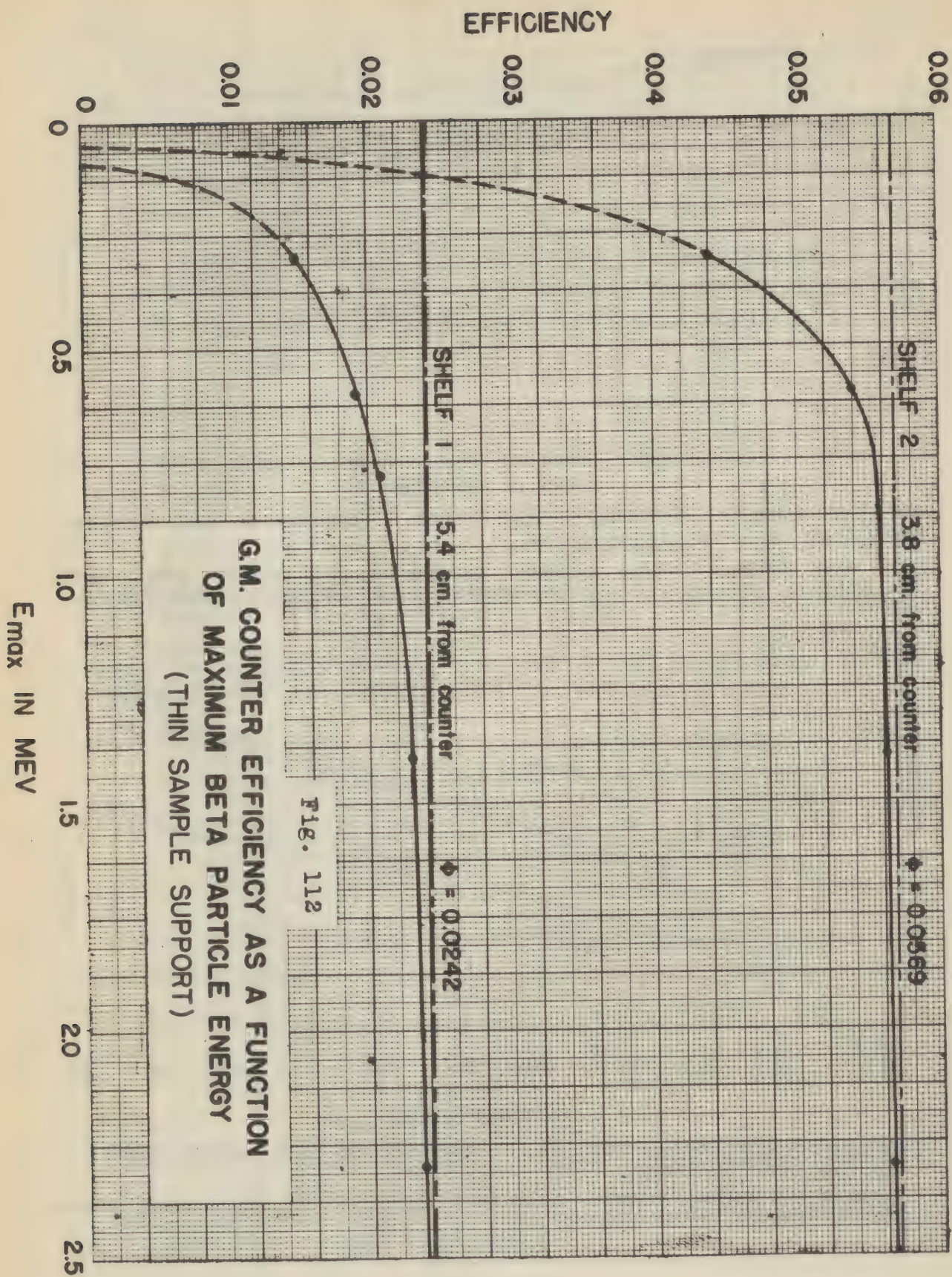


SATURATION BACKSCATTERING AS A FUNCTION OF THE ATOMIC NUMBER OF THE BACKSCATTERER.

ORDINATE REPRESENTS PERCENT OF COUNTING RATE OBTAINED WITH SAMPLE SUPPORT OF INFINITESIMAL THICKNESS.

Fig. 111







## 21. IONIZATION CHAMBER

### A. Description

A gas filled chamber containing an electric field for the collection of charge produced by ionizing radiation is referred to as an ionization chamber when the electric field strength is just sufficient to collect all the initially formed charge. The electric field strength required for charge collection in chambers is generally 20-100 volts per cm. and usually is not critical. This corresponds to the field necessary to collect the ions before appreciable recombination has taken place in the gas and yet it is not high enough to produce additional ion pairs by multiplicative processes as the ions drift to the collecting electrodes. The charge collected therefore, should in principle, just equal the ionization produced directly by the incident radiation and its recoils (see figure 99 ).

All ionizing radiations can be detected with appropriate forms of chambers. In the case of heavily ionizing particles, including electrons in some instances, separate ionizing events can be counted by much the same technic and equipment used for Geiger-Müller and proportional counters. Gamma radiation and usually beta particles are detected by the average accumulation of charge per unit time rather than as discrete events. The details of the construction of an ionization chamber depends, therefore, to some extent on the type of radiation to be detected but frequently its design and construction materials are determined more by the particular circumstances of the measurements. Despite the great variations in design, they are in most instances, built around one of two basic forms of collecting electrode arrangement: either two parallel plates, one

of which is highly insulated and connected directly to the detecting instrument; or a rod shaped collecting electrode mounted coaxially with a cylindrical anode (or cathode).

Chambers designed for detecting radiation by the time rate of accumulation of charge will normally operate satisfactorily with most gases including those that form negative ions such as air,  $\text{CO}_2$  and water vapor. Pulse chambers, on the other hand, frequently give erratic performance and a poor pulse shape in the presence of negative ion forming gases (air,  $\text{O}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{CO}_2$  and the halogens). Usually, they are operated in atmospheres of  $\text{N}_2$ , A,  $\text{CH}_4$ , etc., at atmospheric pressure.

The method employed for measuring the magnitude of the collected charge depends on the application and design of the chamber. In most applications a very high order of sensitivity is desirable and can be achieved with any of several devices to a degree where the limitations on sensitivity is set by the statistical fluctuations in the background. In all the detecting instruments employed with ionization chambers, the physical quantity measured is the small electrostatic field produced by the collected charge. This may be the potential established across a set of electrodes due to the inherent capacitance of the chamber and the instrument together with that of a small capacitor, if one is used, or it may be the voltage developed across a high resistance through which the charge leaks to ground. Although the millivolt is the absolute quantity directly measured, such instruments can be calibrated in terms of roentgens, curies and in units of radiation intensity or source activity.

The instruments most frequently adopted to ionization chamber measurements are summarized below.



1. Quartz fiber electroscope. Of the numerous types of electroscopes developed for radiation detection, the form developed by Lauritzen is the most frequently used in this country. It consists of a metal coated quartz fiber, 6 mm long and 0.005 mm in diameter mounted parallel to a rigid wire and connected mechanically to it as shown in figure . The fiber is initially displaced by charging it with a potential of approximately 100 volts before a measurement is to be made. Then, as ions of the opposite charge are collected, it drifts back at a rate proportional to the rate at which ions are produced. Small displacements of the fiber are very nearly proportional to the number of ions collected and the instrument can be calibrated either in volts per second or in e.s.u. per second.

Normally, the background activity from cosmic rays and alpha particles gives a drift rate of five to ten scale divisions per hour.

2. Moving vane electrometer (1). The most suitable electrometers of this type for ion detection are those with a metal coated quartz fiber mounted on a torsion fiber in the gap between constant potential electrodes. Both the Hoffman (2) and Lindemann (3) forms have been widely used with ionization chambers but at the present time the Lindemann electrometer generally is preferred (see figure 113). It is highly sensitive and can be made portable, and its calibration is independent of its orientation.

With the appropriate electrical circuits the rate of charge collection can be read directly in terms of scale divisions per second or it can be used as a null instrument and calibrated in terms of millivolts per second required to maintain the fiber at the zero position. The latter method is preferable when the highest accuracy is desired.

3. Vacuum tube electrometer. The voltage produced by leakage of the collected charge across a high resistance of the order of  $10^9$  ohms can be amplified by an electrometer connected vacuum tube similar to the method described in the section on the mass spectrograph. Two vacuum tubes have been designed specifically for this purpose; the FP-54 and the victoreen VX-41 (4,5).

D. C. amplifiers have met with only limited use for ionization chambers partly because of the technical difficulties in their construction and operation and partly because of their susceptibility to microphonics, long period drift, and its high noise level as compared to other detecting devices.

4. Vibrating reed electrometer. The vibrating reed is a variable capacitor for converting the D. C. potential developed across a capacitor by the collected charge from the ionization chamber into an A. C. voltage which can be amplified by conventional amplifiers. For a constant charge on the collecting system, the voltage across the capacitor is

$$V = V_0 + \frac{Q \sin wt}{C}$$

Where  $V_0$  is the initial D. C. voltage,  $Q$  the charge,  $C$  the effective reed capacity, and  $wt$ , the vibrational frequency. The A. C. signal which is amplified is then  $Q \sin wt/C$  which increases in amplitude as the charge accumulates. Electrometers of this type are particularly well suited to ionization chambers designed for measuring beta particles, gamma rays and cosmic rays. Aside from the limiting sensitivity imposed by the voltage due to thermal agitation, it is less susceptible to microphonics and some



of the factors which in other electrometers, cause long period drift and high noise level (6).

After amplification, the A. C. voltage is rectified and measured by a recording potentiometer. This provides a considerable advantage in taking measurements since the slope of the recorded trace is proportional to the ionization rate. Further, the incidence of an alpha particle in the chamber produces an abrupt deflection in the slope of the line thus allowing the background of alpha particles to be fully accounted for separately in each sample without resorting to statistical methods.

5. A. C. amplifiers. Heavily ionizing particles such as protons, alpha particles and fission fragments are normally detected in ionization chambers by A. C. pulse amplifiers and counted by conventional recording circuits. The voltage developed across a high resistance of the order  $10^8 - 10^{10}$  ohms is impressed on the grid of a vacuum tube operated usually as a cathode follower i.e., with a cathode resistor of 10,000 - 50,000 ohms. This is followed by one or two stages of amplification and possibly a cathode follower output stage leading to the counting circuits. Considerable precautions must be taken with pre-amplifiers of this sort, to insure good insulation of the grid circuit of the first tube and generally to provide insulation and shielding against vibration and external electromagnetic fields. Miniature tubes of the types 6AK5, 9001, 9002, 945, etc., have proved to be the most satisfactory for this application (7).

#### B. Statistics of Measurements

The probable error of measurements with an ionization chamber recording discrete events is estimated by the same procedure used for other

counting methods and is given in detail in the section on statistics for Geiger-Müller counters. Chambers for detecting beta, gamma and cosmic radiation, on the other hand, requires the measurement of a continuous variable which may be either scale division per second or millivolts per second. The procedure is precisely the same, however, when the terms are redefined.

Assuming only cosmic rays and alpha particles from the chamber walls to be responsible for the observed background, the standard deviation of a single measurement of the background charge taken over a time  $t_b$  is

$$\sigma_b = \frac{1}{\sqrt{t_b}} (a^2A + b^2B)^{1/2}$$

$a$  = average number of ions pairs produced in the chamber per alpha particle.

$b$  = average number of ion pairs produced in the chamber per cosmic ray.

$A$  = average number of alpha particles per unit time.

$B$  = average number of cosmic rays traversing chamber per unit time.

In the presence of the radiation being measured, the standard deviation for a single measurement of the radiation plus background over a time  $t_r$  in terms of charge units is

$$\sigma_r = \frac{1}{\sqrt{t_r}} (r^2R + a^2A + b^2B)^{1/2}$$



$r$  = average number of ion pairs produced in the chamber per incident particle or ray.

$R$  = average number of events per unit time in chamber.

The total standard deviation, therefore, is

$$\sigma = (\sigma_b^2 + \sigma_r^2)^{1/2}$$

Alternatively, a measurement can be expressed in millivolts per unit time by:

$$v_b = \frac{10^3}{Cq} (aA + bB) \text{ mv per sec.}$$

$$v_r = \frac{10^3}{Cq} (rR + aA + bB) \text{ mv per sec.}$$

$C$  = total capacity of collecting electrode plus its external connections, e.g., electrometer fiber and connections or vacuum tube grid and lead.

$q$  = number of ions pairs per coulomb

The standard deviations in terms of mv per second are then:

$$\sigma'_a = \frac{10^3}{Cq} \sigma_b$$

$$\sigma'_r = \frac{10^3}{Cq} \sigma_r$$

$$\sigma'_t = [(\sigma'_r)^2 + (\sigma'_a)^2]^{1/2}$$

When a set of  $N$  measurements have been taken, the standard deviation from their mean value,  $\bar{v}$ , is given by:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (\bar{v} - v_i)^2}$$

$v_i$  = values of individual determinations in units of millivolts.

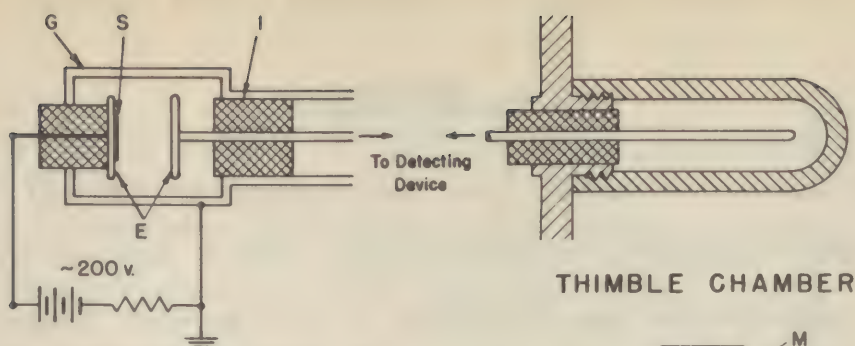
This is calculated for  $N_B$  determinations of the background and  $N_R$  determinations of the measured radiation plus background to obtain the total standard deviation from the mean,  $\sigma_T$ , where, as before

$$\sigma_T = (\sigma_B + \sigma_R)^{1/2}$$

#### References

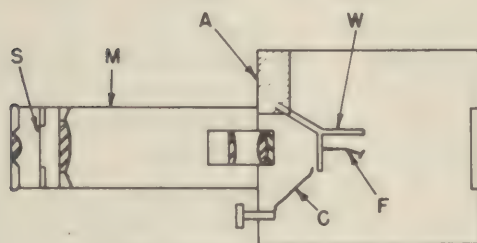
1. Strong, John, Procedures in Experimental Physics. Prentice Hall, Inc., N. Y. (1946)
2. Hoffman, G., Phys. Zeits. 13, 480, 1029 (1922)
3. Lindemann, F. A., Lindemann, A. F., Kerley, T. C., Phil. Mag. 47, 577 (1924)
4. Lafferty, J. M., Kingdon, K. H., J. Appl. Phys. 17, 894 (1946)
5. Nier, A. O. Rev. Sci. Inst. 18, 398 (1947)
6. Scherbatskov, S.A., Gilmartin, T. H., Swift, G., Rev. Sc. Inst. 18, 415 (1947)
7. Parsegean, V. L. Rev. Sci. Inst. 17, 39 (1946)





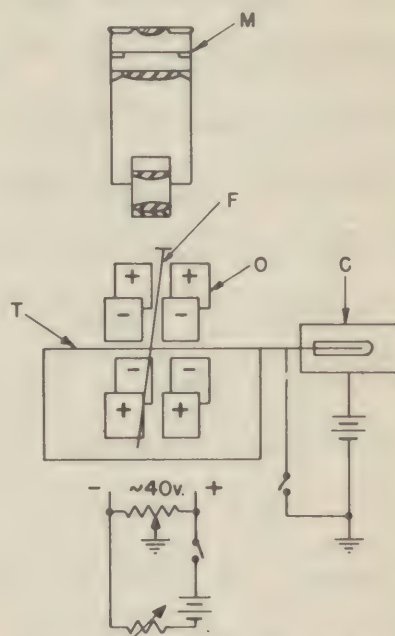
### PARALLEL PLATE IONIZATION CHAMBER

E PARALLEL PLATE ELECTRODES  
G CHAMBER FILLED WITH ARGON OR NITROGEN  
I ELECTRODE SUPPORT INSULATOR OF AMBER, LUCITE, ETC.  
S RADIOACTIVE SAMPLE PLACED ON ANODE.  
ALTERNATIVELY, A THIN ALUMINUM OR MICA WINDOW IN THE SHIELD CAN BE USED FOR ADMISSION OF RADIATION.



### LAURITZEN ELECTROSCOPE

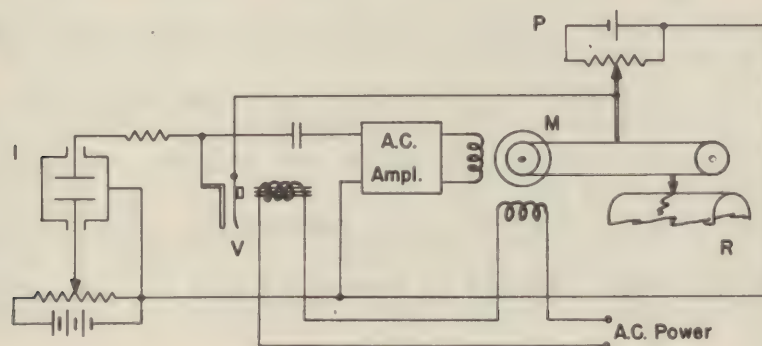
A AMBER SUPPORT  
F METAL COATED QUARTZ FIBER WITH "T"  
FIBER MOUNTED AT FREE END  
C SWITCH FOR CHARGING FIBER  
M MICROSCOPE  
S SCALE FOR READING DISPLACEMENT OF FIBER  
W AMBER SUPPORT



### LINDEMANN ELECTROMETER

C IONIZATION CHAMBER  
F METAL COATED QUARTZ FIBER WITH "T" FIBER AT ONE END  
M MICROSCOPE  
O OCTANTS  
T QUARTZ TORSION FIBER

Fig. 113



### VIBRATING REED ELECTROMETER

I IONIZATION CHAMBER  
M TWO-PHASE MOTOR  
P SLIDE WIRE POTENTIOMETER OPERATED BY MOTOR  
R RECORDING PEN OPERATED BY MOTOR AND CHART PAPER  
V VIBRATING REED AND DRIVING COIL

## 22. INDIRECT METHODS FOR MEASURING STABLE ISOTOPES

### A. Introduction

In addition to the direct, i.e., electromagnetic, methods for the determination of the abundance of stable isotopes, several indirect methods are available. These involve the measurement of some physical property which changes with isotopic ratio. Density and the refractive index are among the suitable properties and have been used to determine the abundance of the heavy isotope of hydrogen, deuterium, in water (1,2,3,4,5,6). Densitometric methods have also been used to study the abundance of the heavy isotope of Oxygen,  $O^{18}$  (7,8). Except in the study of these two isotopes, however, these methods are not likely to become widely applied. The detection of small differences in these properties is difficult and in those cases where there is relatively little difference in the masses of the isotopes involved, even very large changes, say 100%, in isotopic composition cause undetectably small changes in these properties. This fact, together with the complication that traces of impurities may exert comparatively large effects, serves to render these methods useless in most instances.

Water, however, is comparatively easy to purify, and deuterium oxide is 10.7% heavier than ordinary water; a difference sufficiently great to enable one to measure its concentration in moderately high dilutions. Several highly precise methods have been developed which are suitable for such determinations. These will be outlined in the following paragraphs. The problem of preparation and purification of water samples is common to all of the methods and will be discussed first.



## B. Preparation and Purification of Water for Analysis

Although it has been stated that water is comparatively easy to purify, this can by no means be interpreted to mean that extreme care is not essential to the process. The details of a satisfactory procedure have been presented by Keston, Rittenberg, and Schoenheimer (4). In summary, their procedure consists of obtaining water from organic compounds in which deuterium has been introduced as a tracer by burning them on hot copper oxide in a stream of oxygen, the water being collected by condensation in a trap surrounded by dry ice. The water sample thus obtained is then purified by successive distillations in a vacuum train. The first trap usually contains chromic oxide and the second, alkaline permanganate. Upon its collection in the final trap, the water is ready for analysis. Cohn (9) suggests modifying the technic by using Vycor rather than quartz combustion tubes and by using silver gauze plugs in the combustion tube packing. Fetcher (10) uses calcium oxide rather than potassium hydroxide in the second trap.

It is imperative that all glass with which the water comes in contact be scrupulously clean. The recommended procedure is to wash all of the articles concerned with hot solutions of sodium triphosphate, rinse with distilled water, treat them with boiling concentrated nitric acid, rinse about ten times with freshly distilled water, and finally, dry them in an electric oven.

If the sample of water to be analyzed was formed by the combustion method, it is necessary to introduce a small final correction for the natural abundance of the isotope  $O^{18}$  in each of the following procedures.

### C. Refractive Index

The refractive indices of  $H_2O$  and  $D_2O$  differ by 0.00462 for the Sodium D line at  $20^\circ C$  (3). The deuterium content of water can be determined from the difference between the refractive index of pure water and that of the sample. The Columbia University group has used a Zeiss interferometer for this purpose, calibrated to read directly in per cent deuterium (3,4). They report that the deuterium content in 0.4 cc of water can easily be determined with an error no greater than 0.02 atoms per cent (4). A general discussion of refractometry is presented in a brief article by Forrest (11).

### D. Pycnometer

Pycnometers are vessels with capillary necks or with accurately fitting ground glass joint stoppers having a capillary center in which a definite volume of liquid can be weighed. Methods for filling them are described in such texts as that by Daniels, Mathews, and Williams (12). For precision applications, they must be maintained at a known temperature while being weighed. The pycnometer method usually serves as the primary standard for all other methods of deuterium analysis; densities corresponding to an error of the order of 0.001 per cent in deuterium can be measured. The method, however, is not suitable for routine determinations because it is tedious and time-consuming, and requires quite large samples (~ 5 cc). Other drawbacks to its use as listed by Lamb and Lee (13) are that it is difficult to secure a constant and definite temperature inside a considerable volume of unstirred liquid; that because of the variation in humidity of the surfaces of glass vessels, they are difficult to weigh accurately; and that the pycnometer, together with its contents, imposes a considerable load on the balance and therefore reduces its



sensitivity. Some of the difficulties of this method may be avoided by the displacement method in which the vessel is suspended in a liquid while it is being weighed. The additional error introduced by surface tension effects on the suspending wire, however, is sufficient to offset the advantages of this procedure.

#### E. Submerged Float

The submerged float method is based upon the principle that a float can be so critically constructed that at a certain temperature it will neither rise nor sink when immersed in a fluid of a certain density and under a certain pressure. With the proper construction, minute changes in any one of these factors will destroy the equilibrium and the float will either rise or fall. Methods for precise measurements with the submerged float have been described by Richards and Shipley (14), Lamb and Lee (13), and by Gilfillan (14). The first of these workers varied the temperature, the second group used magnetic control, while the third varied the pressure in determining the density of the fluid. The application of the method to deuterium studies is described by Rittenberg and Schoenheimer (3). In their technic, the water to be analyzed is distilled in vacuo into the tube containing the float and the density of this sample is determined by adjusting the impressed pressure until the float begins to rise. From the rate of its rise and fall the equilibrium pressure is calculated. With the pressure set at this value, the float will remain stationary for as long as 15 minutes as observed by reference to cross hairs in the field of a microscope. The pressure change of 1 cm of mercury corresponds to a change in density of 0.376 part per million, or about 0.0003 per cent deuterium.

This method has a high degree of precision and has been used for measurements of concentrations below 0.03%, with successive determinations being made to better than 0.0005 atom % (4). The theoretical errors amount to a cumulative maximum of 3 units in the 7th decimal place (13). The method, however,

is tedious and not readily adapted to routine determinations.

#### F. Falling Drop

The falling drop method consists essentially of determining the density of a drop of water from the rate at which it falls through a non-miscible liquid of slightly lower density. The rate of this fall is determined by a number of factors as expressed in Stokes' law:

$$6 \eta v = \frac{4}{3} a^2 (d - d_0) g$$

$\eta$  = viscosity of medium

$a$  = radius of drop

$v$  = velocity of drop

$d$  = density of drop

$d_0$  = density of medium

$g$  = acceleration due to gravity

It is apparent that if one is to relate the density of the drop to the velocity of its fall, all of the other factors must be rigorously controlled.

The falling drop method was devised by Barbour and Hamilton (16) as a means of avoiding some of the difficulties inherent in the Hammerschlag method for determining density, in which the density of the medium is adjusted by changing its composition until a drop of the sample neither rises nor falls. The original workers used a mixture of bromobenzene and xylene as the medium. It is desirable, however to use a single compound to avoid the differential vaporization which occurs in a binary system. Keston et.al. (4) introduced the use of orthofluorotoluene, which has a density convenient for measuring 0 - 3%  $D_2O$  at 26.8°C. Metafluorotoluene may be used for the same concentration range



at 19.3°C. These tolouences have the further advantage of lower viscosity and therefore greater sensitivity. They are obtainable from the Eastman Kodak Company or may be synthesized by the method used for fluorobenzene (17). In practice, the medium is contained in a tube, the dimensions of which are not critical except that its inside diameter should be greater than three times the diameter of the drop in order to avoid wall effects. The velocity of the drop is obtained by timing the interval during which it falls between two feducial marks on the tube. These lines should be as far apart as practicable to provide maximum sensitivity and best average rate of fall. About 20 cm should be allowed above the top mark to insure thermal equilibrium between the drop and the medium by the time it reaches the first mark, and 8 to 10 cm below the lower mark to avoid end effects.

The tube is mounted vertically in a well-stirred water bath of about 100 liters capacity. The density and viscosity of the medium are controlled through careful thermostating of the bath; the temperature should be held constant to plus or minus 0.001°C. The glass walls of the tube introduce sufficient lag in heat transfer to insulate the medium from minor temperature fluctuations. Sensitive mercury or toluene-filled thermoregulators are satisfactory in most cases (18,19). A temperature is selected which will give a convenient rate of fall for the deuterium concentration range to be studied.

The size of the drop is controlled through the use of a micropipette. The size used by various workers has varied from 5 to 45 cu mm (9) with about the same sensitivities being achieved. Even though the size of the drop is not critical within reasonable limits, it is imperative that those used be of uniform size.

Under the conditions used in this method, the rate of fall does not follow Stokes' law perfectly and it is necessary to establish a calibration curve. The deviation from Stokes law is calculated from the differences between the recipro-

cals of the time of fall of known samples and pure  $\text{H}_2\text{O}$ . (9).

The error involved in this method amounts to about 1 to 4 parts per million. However, errors introduced in the combustion and purification processes raise the overall error to 20 ppm or of the order of 0.02% deuterium (9).

#### G. Diffusion Gradient

The following description is an abstract of an article on the diffusion gradient methods by Chris Anfinson (20).

When one liquid is layered over another of greater specific gravity with which it is miscible, a linear gradient of density develops in the region of the juncture of the two. The density of a drop of water can be determined by introducing it into the region of this gradient and comparing its equilibrium position with that of drops of known density and  $\text{D}_2\text{O}$  content. One advantage of this method over that of the falling drop is the fact that the accuracy of the method is not appreciably affected by convection currents. Nevertheless, accurate thermostating is essential to this method also.

The gradient is prepared from two bromobenzene-kerosene mixtures, the lighter having a density of about 0.99, and the heavier, a density of about 1.02; the density of 10%  $\text{D}_2\text{O}$  having the intermediate value of 1.01. A method is discussed for freeing the mixtures of water and of water-soluble substances in order to avoid exchange of these substances with the drop being tested. The gradient tube, consisting of two bulbs joined by a tube about 2.5 cm diameter and 20 cm long, is filled with the heavier of the two mixtures to the middle of the tube, and the lighter mixture is carefully layered over it to a level in another tube above the second bulb. A uniform distribution of the mixtures is secured in the tube by vertical strokes of a stirrer. The gradient is then calibrated with drops of known composition. In practice, the equilibrium



position of a drop of unknown density is compared with that of drops of known composition and density chosen to bracket the expected density range. An accurate estimate of the deuterium content of the sample can then be calculated by interpolation.

#### REFERENCES

1. Hevesy, G., and Hofer, E., *Nature*, (London), 134:879 (1934).
2. McDougall, E. J., Verzar, F., Erlenmeyer, H., and Gaertner, H., *Nature*, (London), 134:1006 (1934).
3. Rittenberg, D., and Schoenheimer, R., *J. Biol. Chem.* 111:169 (1935).
4. Keston, A. S., Rittenberg, D., and Schoenheimer, R. *J. Biol. Chem.* 122: 227 (1937).
5. Flexner, L. B., Gellhorn, A., and Merrell, M., *J. Biol. Chem.* 144:35 (1942).
6. Moore, F. D., *Science* 104:157 (1946).
7. Dole, M., and Slobod, R. L., *J. Am. Chem. Soc.* 62:471 (1940).
8. Dole, M., Hawkings, R. C., and Barker, H. A., *J. Am. Chem. Soc.* 69: 226 (1947).
9. Cohn, M., *Preparation and Measurement of Isotopic Tracers*, pp. 51-59, J. W. Edwards, Ann Arbor, Michigan (1946).
10. Fetcher, E. S. Jr., *Ind. Eng. Chem., Anal. Ed.* 16:412 (1944).
11. Forrest, J. W., *Medical Physics*, pp. 1214-1224, Year Book Publishers, Chicago (1944).
12. Daniels, F., Mathews, J. H., Williams, J. W., *Experiments in Physical Chemistry*, McGraw-Hill (1941).
13. Lamb, A. B., and Lee, R. E., *J. Am. Chem. Soc.* 35:1666 (1913).
14. Richards, T. W., and Shipley, J. W., *J. Am. Chem. Soc.* 34:599 (1912).

15. Gilfillan, E. S., J. Am. Chem. Soc. 56:406 (1934).
16. Barbour, H. G., and Hamilton, W. F., Am. J. Physiol 69:654 (1924);  
J. Biol. Chem. 69: 625, (1926).
17. Blatt, , Organic Synthesis, Wiley(1944).
18. Swieloslawski, W., Microcalorimetry, Reinhold(1946).
19. Harkins, W. D., and Brown, F. E. J. Am. Chem. Soc. 38:246,(1916).
20. Antinson, Chris., Preparation and Measurement of Isotopic Tracers, pp.  
61-65, J. W. Edwards, Ann Arbor (1946).



## 23. MASS SPECTROGRAPH

### A. Aston Mass Spectrograph

An arrangement of electric and magnetic fields devised and perfected by Aston (1, 2) was the first employed for extensive and accurate measurements of isotope masses. A highly collimated ion beam emerging from the slits  $S_1$  and  $S_2$ , as shown in figure 114, is passed through a strong uniform electric field between two parallel electrodes which deflects the ions by a small angle

$$\theta = \frac{lV}{v^2} \frac{e}{m}$$

$l$  = length of path between plates.

$V$  = deflecting voltage on plates.

$v$  = initial ion velocity.

$e$  = ion charge.

$m$  = ion mass.

The defining vane,  $D$ , then permits only ions within a small prescribed range of velocities to enter the uniform magnetic field  $H$ . The angular deflection in the magnetic field is given by the expression

$$\varphi = L H \left( \frac{\theta}{lV} \frac{e}{m} \right)^{1/2}$$

Separation of ions with different values of  $m/e$ , as well as focusing of identical values, takes place only in the magnetic field. The electrostatic field serves only as a velocity analyser to spread the inhomogeneous ion beam into an energy spectrum before it enters the magnetic field.

For small deflections, the focal points for different values of  $m/e$  lie along the line

$$b = a \frac{2 \theta}{\varphi - 2 \theta}$$

which determines the proper location of the photographic plate used for detection. The mass, or more correctly,  $m/e$ , is determined by the location of ion beam image on the plate with respect to one or more accurately known masses. The relative abundance of isotopes is determined from the comparative intensities of the isotope images.

This type of mass spectroscopy is referred to as velocity focusing since ions with identical  $m/e$  but slightly inhomogeneous energies are focused at a point. Ions entering the electric field at slightly different angles, however, cannot be focused and the ion beam currents are therefore exceedingly small as a result of the beam attenuation required for a high order of collimation.

#### B. Dempster Mass Spectroscope

The original Dempster instrument (3) accomplished the separation of ions with different values of  $m/e$  by deflection of the ions through an angle of 180 degrees in a uniform magnetic field. The ions formed in an ionization chamber, I, figure 114, by electron bombardment are accelerated and focused by voltages applied to the slits  $S_1$ ,  $S_2$ ,  $S_3$ ; imparting a final velocity given by

$$v = (2 V \frac{e}{m})^{1/2}$$

$V$  = voltage difference between slits  $S_1$  and  $S_3$ .



$e$  = ion charge.

$m$  = ion mass.

In the uniform magnetic field, the ions follow circular trajectories normal to the field with uniform linear and angular velocity and at a radius of curvature determined from

$$R = \frac{c}{H} (2V \frac{m}{e})^{1/2}$$

$H$  = magnetic field strength.

This form of spectroscope possesses some advantage in utilizing slightly divergent ion beams, hence, somewhat greater beam currents are available than in velocity focusing instruments. It possesses the disadvantage, however, that energetically inhomogeneous ion beams cannot be properly focused. The ion source, therefore, must provide ions of as nearly homogeneous energy as possible when the greatest accuracy and resolution is required.

The focus at the 180 degree position where the collecting electrode is placed is not a line image but has a natural width,  $\delta$ , given by  $\delta = Ra^2$ , where  $a$  is one-half the angular beam divergence in radians at the source. This places a limit on the separation of two values of  $m/e$  with nearly equal magnitude or alternatively determines the maximum allowable angle of divergence for a required resolution since the separation of the two focii must be greater than the image width, or approximately,

$$a^2 < 2 \left| \sqrt{\frac{m_1}{e_1} \frac{e_2}{m_2}} - 1 \right|$$

Assuming the maximum geometrical resolving power to be defined as

the smallest difference in mass for which two focii are just separated, it is then given by the expression

$$\frac{m}{\Delta m} = 2 a^2$$

This assumes the ion beam to be perfectly homogeneous; if it is not, a term involving  $\Delta V$  must be added.

### C. Mattauch Double Focusing Spectrograph

A comprehensive study of ion optics by Herzog (4) demonstrated that with combinations of electric and magnetic fields it is possible to achieve both velocity and directional focusing. Where the highest resolution and accuracy are required this is essential since ion sources do not provide ion beams which are strictly homogeneous in either energy or direction. Following these principles, Mattauch and Herzog (5, 6) constructed a mass spectrograph which provides direction and velocity focusing over the entire mass range. As shown in figure 115, collimated ions from the source pass through an electric field between condenser plates C, forming an arc of  $31^\circ 50'$ . Again collimated by slit  $S_3$ , the ions enter the magnetic field where they are deflected through an angle of  $90^\circ$ . Directional focusing occurs in the electric field and velocity focusing in the magnetic field.

The voltage applied across the electrodes of the electrostatic analyser depends both upon the geometry and the voltage through which the ions are initially accelerated at the source. For ions which traverse the central path through the analyser, the voltage is given by the expression

$$V = 2 V_0 \log \frac{r_2}{r_1}$$



$V_0$  = ion accelerating voltage at source.

$r_1$  = radius of inner electrode.

$r_2$  = radius of outer electrode.

The axial distance,  $a$ , from edge of the magnetic field where the ions enter, to the point of focus (see figure ) is given by

$$a = \frac{C}{H} \sqrt{\frac{2 m V_c}{e}}$$

$H$  = magnetic field strength.

$m$  = mass of particle.

$e$  = charge of particle.

All masses are focused on a plane making a  $45^\circ$  angle with the axis at the entrance point of the magnetic field. The distance of the focal point along this plane for a particular value of  $m/e$  is then

$$b = a\sqrt{2} = \frac{2}{H} \sqrt{\frac{M V_0}{e}}$$

Hence, the mass scale varies as  $\sqrt{m}$ , and can be readily established from one or more known masses.

The dispersion, assuming  $e$  to be constant, is given by

$$\frac{db}{dm} = \frac{1}{H} \sqrt{\frac{V_0}{em}}$$

and the resolving power is given by the expression

$$\frac{m}{\Delta m} = \frac{a}{2s_1}$$

$s_1$  = source slit width.

$m$  = smallest detectable mass difference at mass  $m$ .

#### D. Bainbridge-Jordan Double Focusing Mass Spectrograph

Directional and velocity focusing is accomplished in a mass spectrograph developed by Bainbridge and Jordan (7), first by deflection of ions in an electrostatic analysing field through an angle of  $\pi/\sqrt{2}$ , and then in a uniform magnetic field through a mean angle of  $\pi/3$  radians. With the geometrical arrangement used, the small dispersion in velocity accompanying directional focusing for ions of a particular value of  $m/e$  is cancelled by the velocity focusing in the magnetic field. The focal plane over a large mass range is not strictly flat but over a considerable range about the exactly focused  $m/e$ , it is sufficiently flat to allow accurate comparison of both mass and abundance. A considerable advantage, inherent to this design of spectrograph, is derived from the accurately linear mass scale for a broad range about the exactly focused  $m/e$ . In some instances this is highly desirable since it greatly facilitates accurate comparison of masses.

The relation between the voltage applied across the condenser plates of the electrostatic analyser and the accelerating voltage for any ion which traverses the central path between the plates is expressed by

$$V_e = 2 V_o \log \frac{r_2}{r_1}$$

$V_e$  = analyser voltage.

$V_o$  = accelerating voltage or energy of ion in central path.



$r_1$  = radius of inner condenser plate.

$r_2$  = radius of outer condenser plate.

In traversing the electrostatic analyser, ions of energy  $V$ , differing slightly from  $V_0$ , are focused into an energy spectrum at the focal plane of the analyser, and again diverge before entering the magnetic field. The linear displacement of an ion from the central path in focal plane of the analyser for an ion of energy,  $V$ , is, to a close approximation, given by

$$Re = 2R_e B$$

$R_e$  = radius of central path through electrostatic analyser.

$$B = \frac{V_0 - V}{V_0}$$

Only those ions in the central path with a particular value of  $m_0/e$  are deflected by the magnetic field through exactly  $60^\circ$  when the magnetic field satisfies the relation,

$$H = \frac{1}{R_m} \sqrt{\frac{2 M_0 V_0}{e}}$$

$R_m$  = radius of ion  $m_0/e$  from central path in magnetic field.

Under these conditions the ion enters and leaves normal to the edge of magnetic field and ions of the same  $m_0/e$  but with different energies are deflected through a smaller or greater angle to be focused at a distance

$\sqrt{3} R_m$  along the central path from the edge of the magnetic field. The displacement of the focus from the apex of the magnetic field along the line OA, for such ions is  $D = 2 R_{m_0}$ . The same displacement for an ion of mass  $m$  is given by

$$D = -\frac{R_m}{2} \left[ \left( \frac{m}{m_0} \right)^{1/2} (1 - B) - 1 + 2B \right] \left[ 1 + \frac{\sqrt{3}}{\tan(\theta_0 + \phi)} \right]$$

$$+ \frac{R_m (1 - B)}{\cos(\theta_0 + \phi)} \left( \frac{m}{m_0} \right)^{1/2}$$

$$\sin \phi = \frac{\sqrt{3} \left[ \left( \frac{m}{m_0} \right)^{1/2} (1 - B) - 1 + 2B \right]}{2(1 - B) (m/m_0)^{1/2}}$$

Actually, only the ion of mass,  $M_0$ , for which  $R_e = R_m$  and which enters and leaves the magnetic field normal to its edge, is focused exactly on this line. The error in the focus for other masses, however, is small for a considerable range of mass about  $m_0$ . The width of the final focus of mass  $m_0$  for which the conditions above hold is

$$\delta = R_m \alpha^2$$

$\alpha$  = one-half angular divergence of beam entering electric field.

$$= \frac{\text{sum of slit widths}}{2 \times \text{slit separation}}$$

The maximum geometric resolving power for ions on the central path, defined as the mass separation equivalent to the width of the focal image (complete separation) can be calculated from



$$\frac{m_0}{\Delta m_0} = \frac{R_m}{\Delta R_m}$$

The resolving power falls off slowly on either side of  $m_0$  due to the increasing image width from imperfect focusing.

### E. Trochoidal Trajectory Mass Spectroscope

A combination of crossed uniform electric and magnetic fields has been proposed which accomplishes complete focusing of ion beams with large initial angular divergence and energy spread (8). Ions injected into a region containing a uniform electric and magnetic field arranged at right angles are known to follow trochoidal trajectories which converge to a single point for any one value of  $m/e$  (see figure 115). The shapes of the ion trajectories in terms of field strengths and initial conditions is given in rectangular coordinates by the equations

$$x = a(\psi - \psi_0) + \rho (\sin \psi_0 - \sin \psi)$$

$$y = L - \rho \cos \psi = (\cos \psi_0 - \cos \psi)$$

$$a = \frac{Ec^2}{H^2} \frac{m}{e}$$

$$b = 2 \pi a = \frac{2 \pi Ec^2 m}{H^2 e}$$

Since  $a$  and  $b$  are proportional to  $m/e$  and not the initial angle or energy, all ions of the same  $m/e$  converge to a point, or a line image, located at a distance of  $x = b$  from the source. It also follows from this that the mass scale is strictly linear over the whole mass range. The secondary generating radius,  $\rho$ , is given by

$$\rho = \frac{1}{r} \left( v_0^2 + \frac{E^2 c^2}{H^2} - \frac{2Ec}{H} v_0 \cos \theta \right)^{1/2}$$

$$\gamma = \frac{eH}{mc}$$

$v_0$  = initial velocity of ion

The resolving power for this type of instrument is given by

$$\frac{m}{\Delta m} = \frac{b}{\Delta b}$$

Ions of different  $m/e$  can be focused on a single collecting electrode by altering the accelerating potential,  $V_0$ , and the deflecting potential,  $V$  ( $= Ed$  where  $d$  is separation of the condenser plates) in direct proportion;  $CV = V_0$  where the constant  $C$  depends upon the design parameters of the instrument. When this condition is fulfilled, ions of any  $m/e$  traverse the same path for the proper values of  $V$  and  $V_0$ .

If the design parameters are chosen to make  $\rho < a$ , the ion trajectory is a curtate cycloid. If  $\rho > a$ , the ion trajectory is that of a prolate cycloid (see figure 115).

#### F. Ion Sources

The ion sources used in mass spectrometers are either high voltage discharges or low energy bombardment by electrons from a hot filament. Both have been widely used and the choice depends to some extent on the application of the mass spectrometer. Some advantage is to be had with the spark discharge source for solid materials since the electrodes can be coated or the electrodes made of the sample material and little difficulty is encountered in producing ions. Furthermore, the construction and operation of this kind of source is usually simpler than hot filament sources.



On the other hand, filament sources regulated with appropriate circuits, give exceedingly stable and reproducible operation over a long period of time and probably produce ions with smaller spread in energy. Particular advantage is gained for the analysis of gases and vapors with these sources since very small quantities need be used for complete quantitative analyses.

1. High-voltage discharge source. Ions may be produced in high voltage sources either by spark discharge in a vacuum chamber or by a steady discharge in an atmosphere of gas at low pressure. The first type of discharge is frequently convenient for the direct ionization of metallic substances. It avoids, among other things, the use of a discharge gas which would produce a spectrum of its own. The sample material can be used as the high-voltage electrode or, when this is impracticable, it can be inserted in a hollow electrode in some usable form; either as a stable salt, alloy, or mixture. Usable high-voltage electrode materials may include all of the metals which are stable in a vacuum at elevated temperatures. The material used, however, should not produce ions with values of  $m/e$  near similar values expected from the sample unless it can be used for a comparison spectrum. The discharge takes place in a small gap between two electrodes which are operated from a tesla coil or some similar high-voltage spark device. Ions which drift to the edge of the discharge in the gap then fall through an accelerating potential maintained between the discharge and a third electrode. This voltage determines the energy of the ions passing through the analyzing fields.

The second type of high-voltage discharge takes place between a grounded cathode and a high-voltage anode in an atmosphere of gas at low pressure. Satisfactory operation is usually obtained with a potential of approximately 15 Kv. Unless the gas itself is to be measured, either neon, or argon are usually used. Ions formed in the discharge column are accelerated toward

the cathode in the electric field of the cathode fall, which extends nearly to the anode or to within a distance determined by the space charge sheath thickness. A portion of the ion beam emerges from the discharge tube through a slot in the cathode and is then collimated by an appropriate arrangement of slits as shown in figure 116 .

Solid substances which are to be analysed may be placed on or near the cathode, or in the case of some metallic elements, the cathode can be made wholly of the sample material. Otherwise it is used in the form of a suitable compound, e.g., as a halide salt if it has a vapor pressure greater than  $10^{-3}$  mm Hg at several hundred degrees centigrade. In general, the combined effects of heating and sputtering by positive ions striking the cathode will ensure an ample concentration of sample material in the discharge for the production of ions.

2. Sources with electron emission from a filament. This type of source is the most widely used at the present time because of its ease of control, stability, adaptability to routine analyses of gases and vapours, and the small energy spread of the ions it produces.

The general scheme of this type of source is illustrated by the examples shown in Figure 116 . The sample material is admitted to a small closed ionization chamber whose dimension are of the order of a centimeter. Ionization is produced by a stream of electrons which enter through a collimating slot at one end, traverse the chamber to be collected at the opposite side by an anode. A fraction of the ions produced diffuse out through a slit in one side of the chamber and are then accelerated in an electric field maintained by an appropriate slit or electrode system.

The filament may be made of tungsten or tantalum and used in the form of a thin ribbon or a helix. Heating currents for filament cross-sections



commonly used is about 5 amperes, a.c. or d.c. Collimation of the electron stream is obtained with the aid of small electro or permanent magnets which provide a field of at least several hundred gauss in the region of the ionization chamber. Electrons emitted from the filament move freely along the lines of force but have low mobility in a transverse direction. On the other hand, ions, because of their greater mass, can cross the field with relative ease when leaving the chamber. Electrons, therefore, leave the filament only in the direction of the anode or electron catcher to which they are accelerated by a potential of about 100 volts. In nearly all cases, the total electron emission is less than 1 ma. Of the fraction of electrons which enter the chamber through the collimating slot, a large proportion are lost either to the walls by repeated collisions with gas molecules and ions, or are captured by ions. The remainder, make their way through the chamber to be collected at the anode. Filaments are operated emission limited and require good thermal regulation to ensure stable operation since the ion beam current is a rather sensitive function of the emission current.

The slit system through which the ion beam passes serves both to accelerate the ions to their final energy before entering the analyzing fields, and to focus the beam to the smallest possible angular spread. Numerous combinations of electrodes have been used to achieve these effects and two examples are shown in figure 116 .

Permanent gases, and vapors of volatile liquids, are introduced directly into the ionization chamber through capillary tubes in which the flow is regulated by a valve or throttling device (9, 10, 11). Solid substances can be analysed usually by one of several methods listed below.

Sublimation or distillation: Some metals, e.g., Li, Ca, Al, Mg., etc.,

and compounds of less volatile elements usually in the form of solids, can be distilled from a hot filament or furnace in or near the ionization chamber.

**Sputtering:** Substances which sputter readily will frequently give a measurable spectrum when a small quantity is inserted in the ionization chamber near the exit slit. This effect can sometimes produce an undesirable background spectrum when light elements are used in the construction of the ionization chamber, e.g., glass, tin, aluminum, etc.

**Carriers:** Heavy metals sometimes can be transported by a stream of chlorine or flourine which forms halides of the metals. Most of these halids, however, condense at room temperature and it is therefore necessary to heat the sample and gas until it entered the ionization chamber.

#### G. Detector Requirements

The accuracy of measurements of relative abundance of isotopes or of the constituents of a sample under analysis depends largely upon the sensitivity, linearity and stability of the device used to measure the focused ion beams of different  $m/e$ . This places severe requirements on the detector since the ion currents may range in magnitude from less than  $10^{-16}$  up to  $10^{-9}$  amperes. Hence, in addition to a high order of sensitivity, the response of an accurate mass spectrograph should be reproducible and dependable over a range of beam intensity of the order of  $10^4$ .

#### H. Photographic Plates

The applications which have required the greatest accuracy have been determinations of isotope mass (relative to  $O = 16.00000$ ) and relative abundance. In nearly all such determinations, photographic plates have been



employed for ion detection. Since they are essentially an integrating device, exceedingly small ion currents can be detected by prolonged exposure, and fluctuations in the current will not affect the accuracy of measurements of relative beam intensities. Both abundance and mass measurements are made from a microphotometric recording of the focal images on the photographic plate. The areas under each intensity curve gives directly the relative abundance and the distance between maxima, the relative masses in the appropriate mass scale for the instrument. When a wide range of beam intensities is analyzed, the response of photographic plates is not linear. In such cases it is nearly always necessary to make several exposures of different values of integrated current on the same plate. For the greatest accuracy calibration of the emulsion response of the plates should be carried out with respect to both the integrated current and also the ion velocity since it is known that the darkening, i.e., number of grains reduced, also varies markedly with the ion velocity. This effect may, therefore, be appreciable over the length of the spectrum photographed at any one time.

Photographic emulsions should be uniform and show little or no fog in development. Further, it is important in abundance measurements that no solarization occur around the most dense images.

### I. Electrical Devices

The earliest electrical devices for detecting ion beams in mass spectrographs were electroscopes and electrometers. These instruments are current integrating devices and hence unsuited to rapid mass analyses. They have, therefore, been wholly replaced by vacuum tube amplifiers which provide the requisite sensitivity but permit less sensitive meters and recording instruments to be used. Most frequently, the first stage of an ampli-

fying system is an electrometer type vacuum tube coupled directly to the ion collecting electrode in the mass spectrometer. Two electrometer tubes with very high sensitivity and suitable characteristics have been developed specifically for this type of application: the PP-54 (12) and the Vx-41 (13). The output current from this stage is further increased by additional stages of d.c. amplification until it has reached sufficient magnitude to operate a galvanometer and recording instruments (13, 17).

The signal voltage driving the grid of the electrometer tube is derived from the voltage,  $E$ , developed across a grid resistor of the order of  $10^8 - 10^{10}$  ohms through which the ion current passes to ground. The maximum sensitivity that can be achieved in circuits of this type is limited by the voltage  $\bar{e}$  produced in the resistor by thermal agitation. This is given approximately by the relation (14, 15, 16)

$$\bar{e}^2 = 4\pi TR \Delta f$$

$T$  = absolute temperature.

$\Delta f$  = frequency band passed by amplifying system.

Assuming the minimum detectable ion current,  $i_0$ , is that which produces across the resistance  $R$  a voltage equal to  $\bar{e}$  then

$$i_0 = 1.29 \times 10^{-10} \frac{(\Delta f)^{1/2}}{R}$$

Values of  $R$  greater than  $10^{11}$  ohms are difficult to obtain and still more difficult to maintain at a constant value. Variations in temperature, and particularly in surface resistance, are sometimes difficult to control and may lead to transient changes in the sensitivity of the instrument. The band pass frequency can be made very small only when the ion current is changed



very slowly. If the mass spectrum is scanned as in most recording mass spectrographs by slowly varying the magnetic field,  $\Delta f$  must be sufficiently wide to allow the comparatively low frequency fluctuation in a current to pass as ion beams of successive values of  $m/e$  reach the collecting electrode.

Considerable care must be exercised in mounting and shielding electrometer tubes. The high sensitivity of this part of the circuit makes it also highly microphonic and sensitive to stray electromagnetic fields. Mounting is best accomplished by carefully shock mounting the tube in a rigid brass or copper can and, in the extreme cases, by evacuating the can to prevent sound transmission and changes in the surface resistance of both the grid resistor and the surface between the tube terminals.

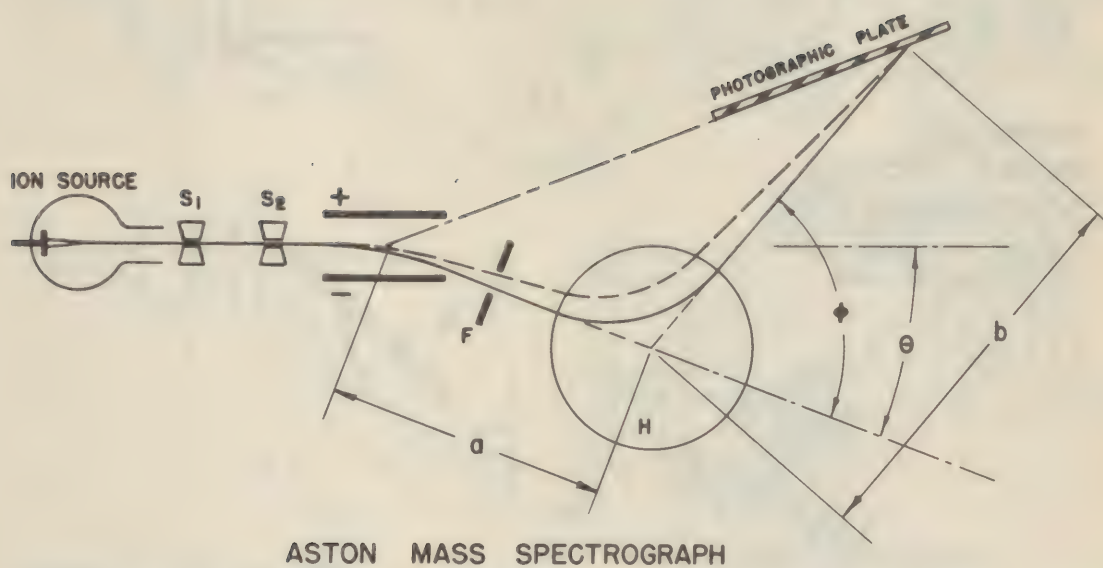
A modified scheme has been proposed by Nier (13) which enables rapid comparison of beam intensity of two values of  $m/e$ , e.g.,  $\text{CO}_2$  44 and  $\text{CO}_2$  45, to be made with considerable accuracy. Two identical d.c. circuits amplify separately the ion currents from two electrodes properly spaced to receive only beams of the two values of  $m/e$  to be measured. After amplification the currents are balanced by an accurate resistor bridge with a galvanometer indicating the null position. The relative beam intensities are then given directly in terms of resistances in the two circuits.

Other detector circuits have been proposed which utilize a.c. amplifiers and a pulsed ion beam to provide an audio frequency signal. In one system, this is done by oscillating the beam radius at a frequency of approximately 200 cps (10). The pulse received by the collecting electrode as the beam sweeps past is amplified and observed on an oscilloscope or alternatively, after amplification it may be rectified to operate a d.c. recording meter. A second scheme accomplishes essentially the same result by pulsing the ion source. (18).

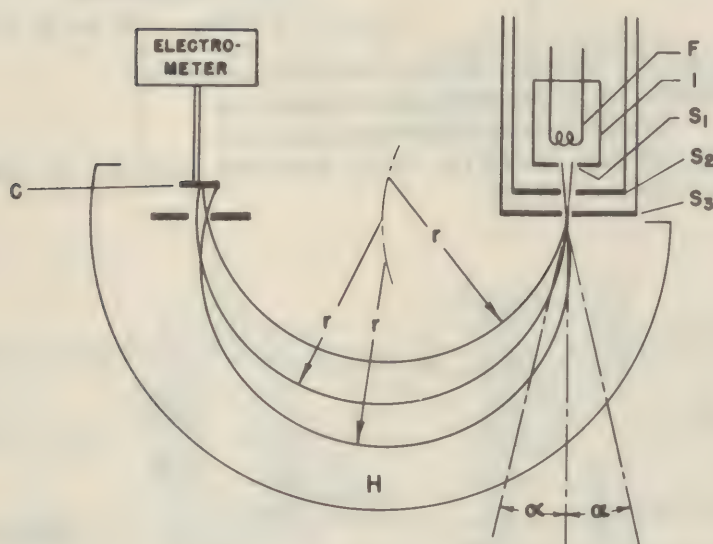
# REFERENCES

1. Aston, F. N., Phil. Mag. 38, 709 (1919).
2. Aston, F. N., Isotopes, Arnold, London(1924).
3. Dempster, A. H., Phys. Rev. 11, 316 (1918).
4. Herzog, R., Ziets. f. Physik, 89, 786 (1934).
5. Mattauch, and Herzog, R., Phys. Rev. 50, 617 (1936)
6. Shaw, A. E., and Rall, W., Atomic Energy Commission, Declassified Document MDDC 45.
7. Bainbridge, K. T., and Jordan, E. B., Phys. Rev. 50, 282 (1936).
8. Bleakney, W., and Hipple, J. A., Phys. Rev. 53, 521 (1938).
9. Nier, A. O., Nery, E. P., and Inghram, M. G., Rev. Sci. Inst. 18, 191 (1947).
10. Siri, W., Rev. Sci. Inst. 18, 540 (1947).
11. Honig, R. E., J. App. Phys. 16, 646 (1945).
12. Lafferty, J. M., and Kingdon, K. H., J. Appl. Phys. 17, 894 (1946).
13. Nier, A. O., Rev. Sci. Inst. 18, 398 (1947).
14. Forrester, A. T., and Whalley, W. B., Rev. Sci. Inst. 17, 549 (1946).
15. Johnson, J. B., Phys. Rev. 32, 97 (1928).
16. Nyquist, H., Phys. Rev. 32, 110 (1928).
17. Washburn, H. W., Wiley, H. F., Rock, S. M., and Berry, C. E., Ind. Eng. Chem., Anal. Ed. 17, 74 (1945).
18. Anker, H. S., Symposium on the Use of Isotopes in Biological Research, Chicago (1947).





ASTON MASS SPECTROGRAPH



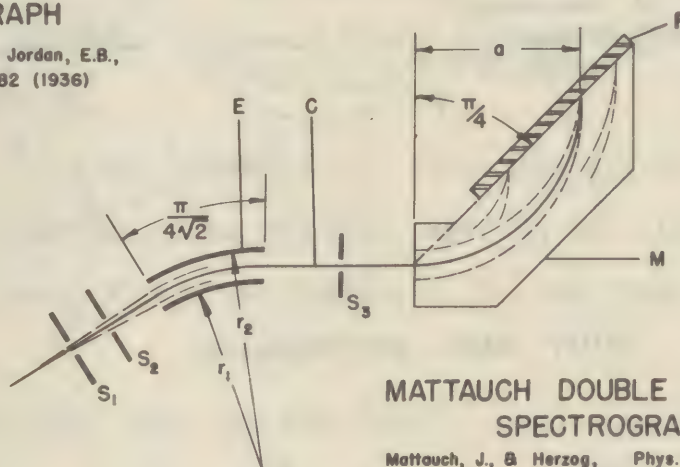
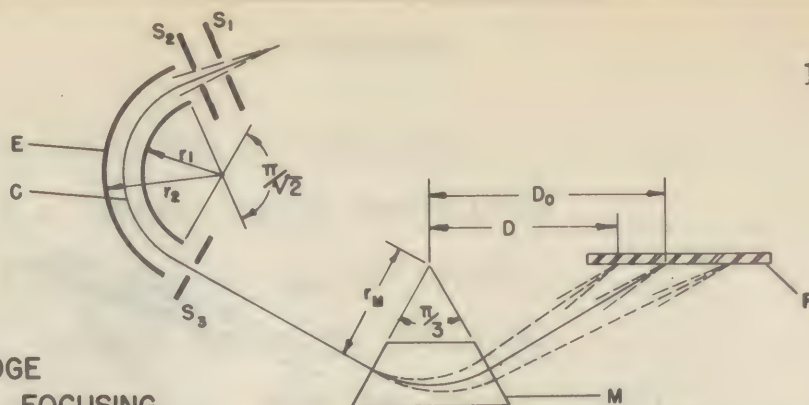
DEMPSTER MASS SPECTROSCOPE

Fig. 114

Fig. 115

# BAINBRIDGE DOUBLE FOCUSING SPECTROGRAPH

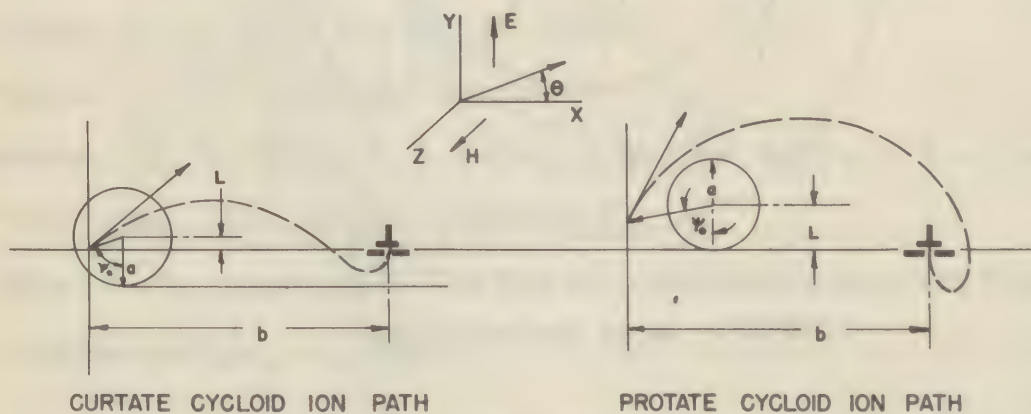
Bainbridge, K.T., & Jordan, E.B.,  
Phys. Rev., 50, 282 (1936)



# MATTAUCH DOUBLE FOCUSING SPECTROGRAPH

Mattauch, J., & Herzog, Phys. Rev., 50, 617 (1936)

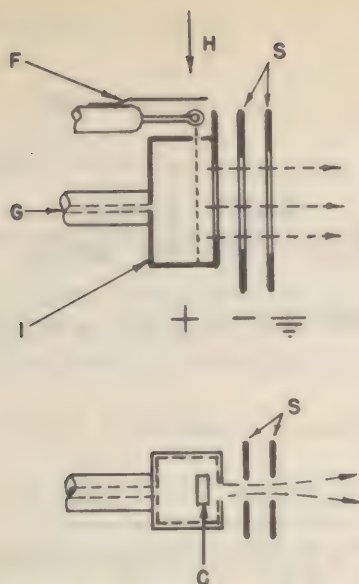
- E DEFLECTING PLATES OF ELECTROSTATIC ANALYSER
- C CENTRAL PATH THROUGH ANALYSERS
- $S_1, S_2, S_3$  FOCUSING AND DEFINING SLITS
- M AREA DEFINING MAGNETIC FIELD DIRECTED NORMAL TO PAPER
- P PHOTOGRAPHIC PLATE



# TRACHOIDAL TRAJECTORY SPECTROGRAPH

Bleekney, W., & Hipple, J.A., Phys. Rev., 53, 521 (1938)

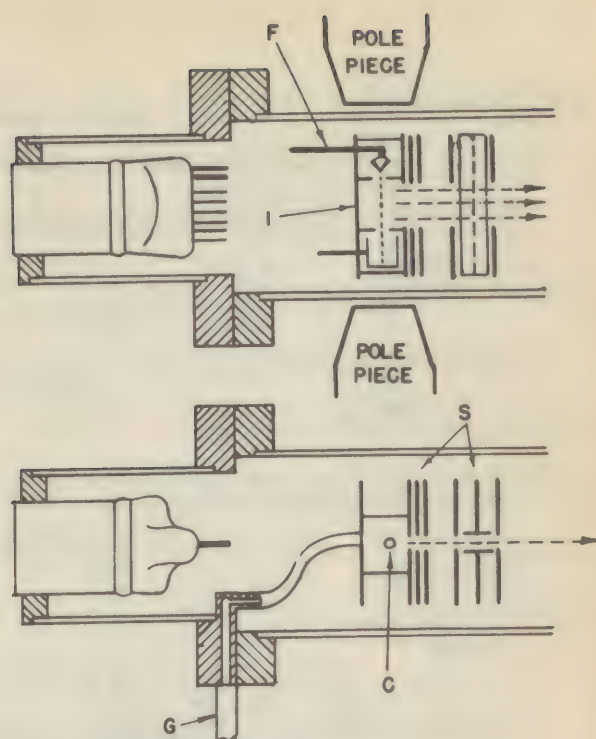




### SIMPLE ION SOURCE

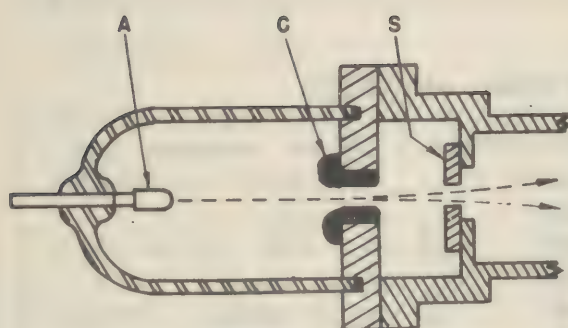
Siri, W., Rev. Sci. Inst., **18**, 640 (1947)

- F FILAMENT
- G GAS INLET TO IONIZATION CHAMBER
- I IONIZATION CHAMBER
- C ELECTRON COLLIMATING SLIT
- S FOCUSING AND ACCELERATING SLITS



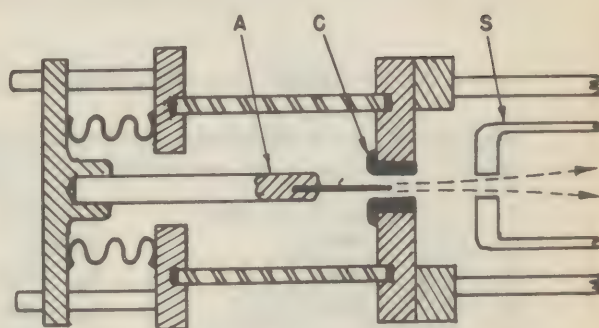
### NIER ION SOURCE

Nier, A.O., Rev. Sci. Inst., **18**, 398 (1947)



### HIGH VOLTAGE GAS DISCHARGE ION SOURCE

Beinbridge, K.T., & Jordan, E.B., Phys. Rev., **50**, 282 (1936)

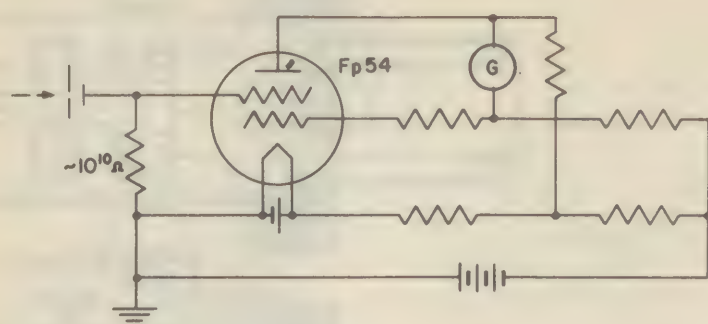


### SPARK DISCHARGE ION SOURCE

Shaw, A.E., & Reil, W., A.E.C. No. MDDC45

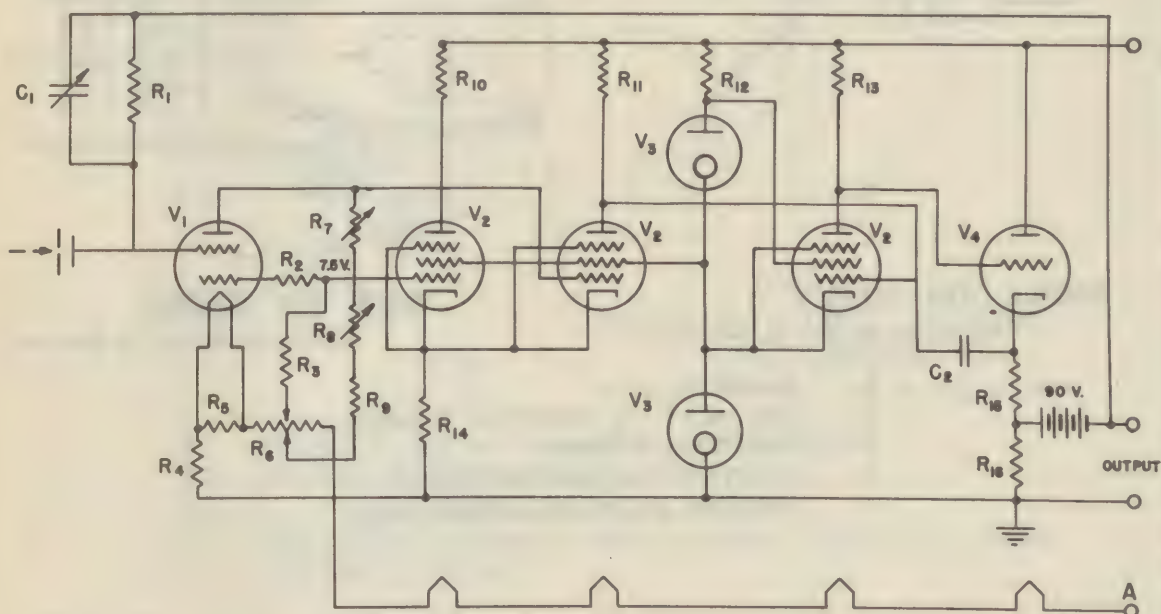
- A ANODE
- C CATHODE
- S ION BEAM COLLIMATING SLIT

Fig. 116



# BARTH-PENICK ELECTROMETER CIRCUIT

PENICK, D.B., REV. SCI. INST., 6, 115 (1935)



## NIER D.C. INVERSE FEED-BACK AMPLIFIER

VOLTAGE AT A IS ADJUSTED SO THAT FILAMENT CURRENT IS 150 MA. PRECISION WIRE WOUND RESISTORS ARE INDICATED BY PWW.

$R_1$   $4 \times 10^{10}$  IRC TYPE MG-6  
 $R_2$  5000 PWW  
 $R_3$  20K PWW  
 $R_4$  40 WIRE WOUND  
 $R_5$  SHUNT TO LIMIT CURRENT THROUGH TUBE TO 20MA.  
 $R_6$  12 STEPS OF 13 OHMS WIRE WOUND

$R_7$  200K POT.  
 $R_8$  20K POT.  
 $R_9$  200K PWW  
 $R_{10}$  1 MEG. 1 W.  
 $R_{11}$  1 MEG. 1 W.  
 $R_{12}$  7500 10 W.  
 $R_{13}$  1 MEG. 1 W.  
 $R_{14}$  35K PWW

$R_{15}$  10K PWW  
 $R_{16}$  15K PWW  
 $C_1$  100  $\mu$ f VARIABLE  
 $C_2$  0.02  $\mu$ f 400 V.  
 $V_1$  VX-41 (VICTOREEN INST. CO.)  
 $V_2$  12SJ7  
 $V_3$  VR75  
 $V_4$  12J5

NIER, A.O., REV. SCI. INST., 18, 398 (1947)

Fig. 117



## RADIOACTIVE ELEMENTS

Methods for ashing plant and animal tissues have been described by many workers. Descriptions of satisfactory ashing methods are usually included with the corresponding analytical procedures, frequently with only slight variations from previously reported work. There are, therefore, very nearly as many ashing technics in biological work as there are methods for the estimation of inorganic elements. Since it is doubtful whether any one procedure can be said to be superior to the rest, only a general description of ashing technics, together with a few typical examples will be given. It should be possible to devise, from the information given, a method which will meet the specific requirements of a particular problem.

A glance at the two tables copied from Hawk will show the relative amounts of inorganic elements which are to be found in human tissue ash (11) and in blood (12).

Table 23 . INORGANIC COMPOSITION OF HUMAN BLOOD

Constituent	Normal Range mg./100 ml.
Chlorides as NaCl	450-500
Sulfates, inorganic, as S (Serum)	0.9-1.1
Phosphorus, inorganic, as P (Plasma)	3-4
Iron, as Fe	52
Copper	0.05-0.25
Calcium (Serum)	9.0-11.5
Magnesium (Serum)	1-3
Sodium (Serum)	330

Constituent	Normal Range mg./100 ml.
Potassium (Serum)	16-22
Iodine (micrograms per 100 ml.)	8-15

Table 24 .

Inorganic Composition of Man

Element	Per Cent	Approximate Amount, in grams, in a 70-Kg. Man
Oxygen	65.0	45,500
Carbon	18.0	12,600
Hydrogen	10.0	7,000
Nitrogen	3.0	2,100
Calcium	1.5	1,050
Phosphorus	1.0	700
Potassium	0.35	245
Sulfur	0.25	175
Sodium	0.15	105
Chlorine	0.15	105
Magnesium	0.05	35
Iron	0.004	3
Manganese	0.0003	0.2
Copper	0.0002	0.1
Iodine	0.00004	0.03



In selecting ashing and purification procedures, the normal presence of these elements must be taken into consideration. The concentrations of calcium, magnesium, sodium, potassium, phosphorus, chlorine, sulphur, etc., in the ash will greatly influence their own recovery and that of other elements present in trace amounts. These concentrations will also dictate the course to be followed in the subsequent analytical procedures.

#### A. Dry Ashing

Ashing at 500-800° is generally carried out in platinum, porcelain, vycor, or nickel crucibles, although in general, platinum is to be preferred. It can not be employed, however, if fluxes are used which contain such materials as potassium acid sulfate, sodium peroxide or hydroxide, excessive amounts of potassium nitrate, or any compounds likely to liberate free chlorine. Such fluxes are not usually encountered in biological work, but if they are needed, it is advisable to use porcelain or vycor, providing that etching due to alkali is not objectionable. Admixtures of such materials as magnesium acetate, calcium hydroxide, etc., will not result in attack on the platinum. If the dissolution of ash requires the use of aqua regia, porcelain or vycor must be used, while platinum is indicated when hydrofluoric acid is employed.

One of the most difficult problems encountered, when porcelain is used, is the fusion of the inorganic material with the crucible; this is a particularly undesirable characteristic of some animal tissues. While the loss of a small portion of the sample, due to crucible fusion, may not appreciably affect the analytical results, it may preclude the subsequent use of this crucible. The danger of cross contamination, due to residual activity in laboratory glassware, must be kept in mind at all times; crucibles showing

unremovable residual activity should, therefore, be discarded. Furthermore, if fusion occurs, recovery of the ashed material is not only difficult, but time-consuming. Vycor and platinum are more satisfactory under these conditions, although, from an economic standpoint, it may be less expensive to use porcelain and to discard the crucibles if appreciable activity remains in them.

For dry ashing, the muffle furnace, which has heating elements at the sides as well as top and bottom, is much to be preferred to gas burners. Not only is the ignition more convenient but it is also more uniform, due to simultaneous heating of the crucible from all sides. The muffle furnace has a disadvantage, however, when completely filled, in that the available oxygen inside is rapidly exhausted. When this condition is reached, the combustible gases produced will leave the furnace as a tarry and soot-laden smoke; the latter must usually be removed by forced ventilation. To avoid this and to aid in combustion, oxygen may be introduced into the furnace through the thermocouple housing, using a quartz tube. When this procedure is followed, the heating units must be reversed, if possible, so that the coils do not face toward the inside of the furnace, and, furthermore, the stream of oxygen must not be directed onto the thermocouple itself.

The general ashing procedure consists of air drying the weighed sample at a temperature of 100° or slightly less, followed by ignition at 500-800° for a minimum of 2 hours. Samples which have been ground or macerated may be dried at reduced pressures; 100 mm. or less is recommended for grain and stock feeds, meat meal, plant tissues, etc., (13). Caution must be exercised in drying whole tissues, such as liver, since they tend to swell at elevated temperatures and, or, reduced pressures. Temperatures above 100° are permissible for removing the last portions of water and volatile oils.



Drying by means of overhead radiant heating has been found to be particularly useful with nearly all types of biological tissues, as well as with solutions of both organic and inorganic compounds.

In many cases the material to be ashed is already dry enough to place in the muffle furnace. Ground grains, bone, and the woody portions of plants, for instance, seldom need to be dried before ignition.

When possible cross contamination or contamination of the muffle furnace is likely to influence the results, it is best to place the samples in a cold furnace and to allow the temperature to rise gradually to the value desired. Rapid ashing produces volatile gases at rates which are sufficient to carry small amounts of the material out of the crucible. Thus, radio-active deposits will collect on the walls and floor of the furnace as well as in the adjacent crucibles.

The duration of ashing, and the temperature, must be considered in relation to the volatility of certain compounds. For example, some iron generally will be lost as ferric chloride, phosphorus as phosphoric acid, sulfur as sulfur di and trioxide, fluorine as hydrogen fluoride or silicon tetrafluoride, chlorine as hydrogen chloride, etc. Because of the difficulty of completely mixing samples with additives which are designed to prevent these losses, 100% recovery of some elements is impossible. From a quantitative standpoint these losses may be inconsequential, but they must be considered in light of the possibility of serious radioactive contamination. Wherever feasible, therefore, wet ashing should be considered if the radioactive element is likely to be volatilized at muffle furnace temperatures.

For radioactive tracer studies, ashing to constant weight is not important. The aim is solely to decompose the tissue to the point where organic compounds, which are likely to interfere in the subsequent analysis, are

completely decomposed. Ashing beyond this point, or to oxidize the last traces of carbon, is unnecessary and wasteful of time. Further investigation of minimum temperature and time for elimination of organic compounds is indicated. The use of perchloric acid after such incomplete ashing should not only be safe, but should also facilitate the dissolution of the inorganic salts. The loss of important elements from the tissue ash might very well be eliminated by this less vigorous procedure; compounds difficult to dissolve should not be produced so frequently.

Aids to ashing have been employed with considerable success. Calcium nitrate, magnesium acetate, and mixtures of calcium and aluminum nitrates may be advantageously used. These salts act not only to supply oxygen, but they also increase the bulk of the ash and render it more amenable to dissolution. The use of these aids is indicated with samples producing little or no ash of their own; for example, fatty tissues and carbohydrates. Magnesium acetate in alcohol is particularly recommended for use with such finely ground material as flour (14). Fusion of material with the crucible is practically eliminated when ash-aids are employed. Etching of the glaze on porcelain is not completely prevented, however, and chlorine attack on platinum, due to oxidation of chloride by nitrate, is likely to occur.

#### B. Wet Ashing

Less drastic than furnace ignition, but more satisfactory in many respects, are the procedures for oxidation of organic material in solution. Wet digestion may require more attention and will frequently be slower than dry ashing, but, on the whole, these disadvantages are more than offset by the superior results obtained when the quantitative recovery of certain elements is desired. The choice between wet and dry ashing is based, therefore, upon



consideration of the likelihood of loss by volatilization at higher temperatures versus the inconvenience in increased time and labor of digestion at lower temperatures. Maximum wet digestion temperatures are governed by the boiling point of the solution in which this digesting occurs, providing the samples are not taken to dryness, and are roughly 400 to 500° C lower than the usual minimum dry ashing temperatures.

The Kjeldahl procedure, with modifications, utilizes concentrated sulfuric acid as an oxidizing agent and has been by far the most widely used method of digesting plant and animal tissues. In addition to this acid, potassium sulfate or persulfate together with a catalyst such as copper, mercury, or selenium, are generally employed. Perchloric acid, as shown below, may be used to great advantage with sulfuric acid, as a modification of the original Kjeldahl method.

Nitric acid and mixtures of nitric acid with hydrochloric acid, hydrogen peroxide, or perchloric acid, have been successfully applied in wet ashing procedures, and are to be preferred whenever the introduction of excess sulfuric acid or sulfates is disadvantageous.

Extensive work has been carried out by Smith (15) and by Kahane (16) on the use of perchloric acid for the digestion of organic material. The former author's publication includes a review of the literature through 1940, and a compilation of some of the more important procedures employing this reagent in conjunction with sulfuric and with nitric acid. Since these procedures are of considerable value to the biologist, the principles upon which they are based, as outlined by Smith (15), are quoted herewith in detail.

"Cold dilute or concentrated perchloric acid is not reduced by organic matter, nascent hydrogen, by electrolysis or catalytic hydrogenation, by hydrazine or hydroxylamine or Devarda's alloy, sodium amalgam, hypophos-

phorus acid, or sodium hydrosulfite. Perchloric acid is quantitatively reduced by a large excess of titanous ion only after long continued boiling. Organic matter from certain animal and vegetable sources can be oxidized at the boiling temperatures of 70-72 per cent perchloric acid only after an hour to several hours' boiling. For example, coal requires from 1-3 hours' boiling and leather an hour or more for complete destruction of the organic matter. In these cases the reaction for quantitative determination of metallic or non-metallic elements must be hastened by the use of catalysts, such as chromium, vanadium, or osmic acid. Large amounts of elemental sulfur are safely oxidized by boiling with concentrated perchloric acid."

"Hot concentrated perchloric acid (60-72 per cent) reacts with explosive violence with organic matter from many sources. Inorganic reducing agents such as hypophosphorus acid, hydroxylamine, and hydrazine, explode with hot, concentrated perchloric acid. Oxidizable metals such as chromium, vanadium, and iron are smoothly oxidized by hot concentrated perchloric acid to chromic and vanadic acid and ferric iron only at temperatures in the range of 200°C. In these cases the excess oxidizing agent is made inactive by the simple process of cooling to ordinary temperatures. In this manner the oxidized elements are determinable, using the ordinary standard reducing agents without the slightest interference from the excess perchloric acid."

"If organic matter reacts violently by boiling with hot, concentrated perchloric acid the reaction intensity is effectively slowed down by the following methods:

1. Dilute perchloric acid (40-60 per cent) is added to the organic matter and the mixture concentrated slowly by heating until the 70-72 per cent strength is attained. The range of concentration governs the speed of oxidation of the organic matter.



2. Nitric acid (sp. gr. 1.42) is used to destroy the easily oxidized portion of the organic matter, after which concentrated (72 per cent) perchloric acid is added and the remaining difficulty oxidizable material quietly oxidized at the boiling temperature, approximately 200 degrees C.

3. A mixture of concentrated nitric and perchloric acids is heated with the organic matter.

4. Concentrated perchloric acid is diluted by the addition of strong sulfuric acid. A suitable mixture consists of one volume of 72 per cent perchloric acid diluted with two volumes of 80 per cent sulfuric acid.

5. A mixture of concentrated nitric, perchloric and sulfuric acids is employed.

6. For the destruction of organic matter in large amounts a digestion with concentrated sulfuric acid at approximately 200 degrees C is treated dropwise by the addition of concentrated perchloric acid as fast as it is consumed. Animal organisms such as liver, brain, and kidney in amounts up to and including one kilogram have been effectively oxidized in this manner."

"Other properties of perchloric acid in addition to the above add to its advantages for the various quantitative applications in which it is employed. All metallic perchlorates are soluble in water and in a great variety of organic solvents. Hot, concentrated perchloric acid is a strong dehydrating agent, for example, silicic acid is quantitatively dehydrated. By the processes for the destruction of organic matter as described the following elements are retained quantitatively, P, S, Si, Fe, Cr, Al, Ca, Mg, and K. Under special conditions arsenic is quantitatively retained."

In his publication, Smith quotes as follows from the work of Kahane (16): "These descriptions give a somewhat incomplete idea of the variety of

procedures which are possible of utilization. In reality there are advantages to be derived from the use of perchloric acid in all wet oxidations at temperatures of 150-200 degrees C, in which range its oxidizing power is effective. Perchloric acid then brings to bear an exceptionally rapid dissolving and oxidizing reaction in cases previously considered difficult to master. On the contrary the operator must follow strict rules in order to avoid unfortunate accidents. It is not necessary to know these rules when a series of known procedures are being followed such as those described in this work, but it is indispensable to assimilate them before attempting original research concerning the use of perchloric acid in unexplored fields or under conditions notably different from the usual case . . . ."

"The advantage which it is important to bring out in the first place is the rapidity of the destruction of organic matter using perchloric acid. The duration of the reaction is naturally variable with the nature of the heating and it is necessary to carry out a given operation several times to attain maximum rapidity. It varies, likewise, with the nature of the substance and the technique of destruction adopted. . . The attack is generally more rapid on vegetable substances such as cellulose or starch, it is slower with fat laden materials. It is very slow with oils and especially so for those rich in carbon."

In concluding his discussion, Smith states: "A few additional facts should be kept in mind using concentrated perchloric acid as oxidizing agent. Hot, concentrated perchloric acid in addition to its oxidizing properties is an efficient dehydrating agent. Therefore, a mixture, of, for example, glycerol and perchloric acid when hot is the equal of glycerol plus nitric acid plus sulfuric acid. The hot, dehydrating perchloric acid serves to esterify the glycerol and as a result the strongly oxidizing



$\text{ClO}_4^-$  group is introduced into the molecule. Whether or not the perchloric acid ester of glycerol is equal in explosive power to nitroglycerine is not known. The corresponding ethyl ester of perchloric acid is violently explosive."

"Organic molecules that contain hydroxy-groups might be predicted to reach with violence in the presence of hot, concentrated perchloric acid. Hydrocarbons such as paraffin, rubber, and rosin might be considered safe while sugar, starch, cellulose, etc., are easily broken down by the preliminary action of nitric acid with rapid and complete destruction by the subsequent perchloric acid effect. Succinic acid might be considered as similar to a hydrocarbon and tartic acid as intermediate between an hydroxyl compound and a hydrocarbon. Organic ring nitrogen compounds are the most difficult to oxidize of all types. Coal for example requires the addition of catalysts to speed up its destruction by hot perchloric acid, if excessive time periods are not to be required."

"The question of the use of filtrates from quantitative separations in which such reagents as cupferron and 8-hydroxy-quinoline, etc., have been used previously as precipitants, often requires destruction of the organic matter prior to subsequent operations. Filter paper, cellulose or cotton are frequently desirable of decomposition to recover mineral constituents absorbed by them. Such problems as the removal of tartaric acid from a solution in which it has been used to prevent precipitation of iron, for example, are frequently met. These and many similar problems are readily and efficiently solved using an attack by sulfuric acid and perchloric acid or perchloric acid alone."

## 25. THE PREPARATION OF THIN FILMS OF RADIOACTIVE ELEMENTS BY ELECTROLYSIS

### A. General Considerations

Although many methods have been proposed for the preparation of thin films which may be used for radioactivity measurements, probably the most convenient and satisfactory is the electrolytic. Under properly controlled conditions it is possible either to electroplate or to electrodeposit many of the elements quantitatively from solutions of their salts and the resulting film can be made quite uniform in thickness. If the apparatus is correctly designed, the area which this film covers will be both accurately fixed and reproducible.

With certain minor modifications, the electrolytic methods generally employed for quantitative chemical analysis are readily applied to radio-assay. For the most part, these methods are for electroplating rather than electrodepositing. The term "electroplating" is usually taken to mean the formation, by electrolysis, of a closely adhering metallic film. "Electrodeposition", on the other hand, may have this same meaning, or it may refer to the electrolytic formation of a non-metallic layer, closely adherent or not, on the electrode. It is in the latter sense that it is employed here.

### B. Electroplating

If two conductors are placed in a solution of an electrolyte, such as sodium chloride, with one conductor connected to the positive pole of a storage battery, and the other to the negative, it will be observed that gas bubbles will be formed on both conductors. These positive and negative conductors, or electrodes, are referred to as "anodes" and "cathodes", respectively, and the reactions which occur on them are known as electrolysis: -



Anode reaction:  $2\text{H}_2\text{O}$  minus  $4\text{e}^-$  ----  $\text{O}_2$  (gas) plus  $4\text{H}^+$

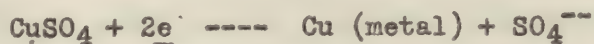
Cathode reaction:  $4\text{H}_2\text{O}$  plus  $4\text{e}^-$  ----  $2\text{H}_2$  (gas) plus  $4\text{OH}^-$

Thus it will be seen that oxygen gas is formed at the anode, and the solution surrounding it becomes acidic, while hydrogen gas is formed at the cathode, where the solution becomes alkaline. In analytical practice, the solution is continuously stirred so that the excess of acid ( $\text{H}^+$ ) and alkali ( $\text{OH}^-$ ) neutralize each other, again forming water. The number of electrons,  $\text{e}^-$ , which are taken away at the anode exactly balance the number added at the cathode. The corresponding chemical reactions are known as "oxidation" and "reduction", respectively. Thus, oxygen atoms with a valence of - 2 are oxidized to zero charge at the anode, while hydrogen atoms with a charge of + 1 are reduced to zero charge at the cathode.

Table 24a. ELECTROLYSIS TERMINOLOGY AND REACTIONS

Electrode name	Battery connection	Electron direction	Chemical reaction	Valence change	Examples
Anode	Positive	Sol. to Anode	Oxidation	Increase	$\text{Fe}^{++} \rightarrow \text{Fe}^{+++}$ , $2\text{Cl}^- \rightarrow \text{Cl}_2$
Cathode	Negative	Cathode to sol.	Reduction	Decrease	$\text{Fe}^{+++} \rightarrow \text{Fe}^{++}$ , $\text{Fe}^{++} \rightarrow \text{Fe}$

If the solution being electrolyzed contains copper sulphate instead of sodium chloride, then, at the cathode reduction of copper will occur, forming a "plate" of metal:



While this reaction is occurring, hydrogen ions will also be reduced at the cathode. Since these two reactions occur simultaneously, the equivalent

ratio of gas formed to metal plated will give a measure of the efficiency of the plating reaction. In practice 100% plating efficiency is rarely achieved; indeed, the plating efficiency decreases nearly to zero as the metallic ion concentration in the solution is reduced. For this reason it may often take very much longer to plate the last 100 micrograms of a 10 mg. sample, than it does to plate the first 9.9 mg. The efficiency of electroplating may be increased toward the end, however, by raising the solution temperature, i.e., by increasing the ionic mobility.

Among the elements which have been successfully electroplated from aqueous solution, are Cu, Ag, Au, Zn, Cd, Hg, Sn, Pb, Sb, Bi, Cr, Fe, Co, Ni, and Pt. Al and several other metals, which are not reducible in aqueous solution, may be plated from organic solvents. In the group of electro-deposited elements are, among others, U, O, and F, as  $\text{UO}_2$  and  $\text{UF}_4$ , and Th, Fe, C, and N, as  $\text{ThFe}(\text{CN})_6$ . Quantitative procedures for electrolyzing most of these elements are well known, although only a few have, as yet, found use in radio-chemistry.

In general, the methods for commercial electroplating can not be successfully applied in analytical work, although the chemical principles and reactions of both procedures may be identical. This is true, essentially, because the conditions of temperature, ionic species and concentration, current, voltage, etc., required for quality plating, do not necessarily satisfy the requirements for quantitative recovery. It is advantageous, however, to obtain a smooth, shiny film whenever possible. Rough films are likely to be porous and may therefore occlude extraneous salts from the electrolysis solution. Colloids are frequently used to improve the electroplate, but no specific rules can be given to govern their use.



### C. Apparatus

Many types of electrolysis cells and stirrers have been designed and used by the various groups which are investigating the field of radio-assay. Unfortunately, many of these developments, like those of the chemical procedures, have not found their way into the published literature.

The simplest electrolysis apparatus will have a rotating anode of platinum or platinum-10% iridium wire. This wire is usually coiled in a flat spiral, and serves both as a conductor and a stirrer. A platinum dish contains the electrolysis solution and serves as the cathode. Alternatively, cathodes consisting of thin discs are probably the most convenient for both gravimetric and radiometric measurements. 1" or 1-1/2" diameter cathodes are most frequently employed. These vary in thickness from 0.0005" to 0.005", depending upon the cost of material, the ease of handling, and the effect of background scattering on the counting rate.

A glass cylinder and gasket, each having the same i.d., and o.d. of either 1" or 1-1/2", generally constitute the body of the cell. The base is constructed so that it either serves for the cathode connection itself, or a separate connection is incorporated in it. Finally, some means must be provided to hold the glass tightly against the base with the gasket and cathode in between.

### D. Anodes

Platinum wire or gauze anodes have been almost universally used for laboratory electrochemical reactions, principally because they are very passive. Platinum has some limitations, however, of which cost is not the least. Electrolysis of acid chloride solutions produces free chlorine at the anode and in the presence of this gas, platinum loses its passivity to

some extent and small but appreciable amounts are dissolved. This reaction increases with hydrochloric acid concentration, temperature, and current density, but is minimized if the platinum is alloyed with 10% iridium.

Similar attack occurs if electrolysis takes place in an alkaline solution containing free ammonia. This attack will not be very great if the current density and ammonium hydroxide concentration can be kept low; it may account for cathode deposits of 0.1 to 0.2 mg. if lengthy electrolyses are carried out, however.

Substitutes for platinum have not proved too satisfactory for quantitative analytical work, since most are attacked in either acid or alkaline solution. If the cathode film need not be weighed, alloys of the 18-8 variety of stainless steel sometimes may be used; carbon or graphite may be employed if anodic oxygen is not formed and if the rods are not appreciably porous. Tantalum can not be used because it forms an oxide coating which prevents the flow of current from solution to anode, although the reverse process occurs with ease.

#### E. Cathodes

The selection of a satisfactory metal for electroplating or electrodeposition depends largely upon whether gravimetric as well as radiometric assay determinations are to be made. If the cathode film is to be weighed, it is best to employ platinum discs; if not, copper, iron, etc., may be used. Furthermore, if the film is to be ignited or calcined, platinum is to be preferred; it must be used if both heating and weighing are necessary, or if the film is later to be recovered quantitatively and pure. In most cases gold may be substituted for platinum, and it is frequently



more economical to do so.

It is generally assumed that cathodes of gold or platinum will be cleaned off and reused. Under some conditions it may be impossible to remove completely the radioactive film, in which case the discs must be discarded, or the activity of each recleaned disc must be recorded before it is next used. When these alternatives are either impractical or uneconomical, gold-plated copper discs may be substituted. A commercial plate of 0.0001" is relatively inexpensive. The plating process is usually carried out using strips of shim stock copper, exposing both sides, and the discs are punched out later. After use, the plated gold may be reclaimed, although it is safer to discard the discs rather than to reuse the recovered gold since the latter may contain contaminating radioactivities.

While most of the elements which can be electroplated will plate out on, and adhere to, copper, platinum and gold, there is no hard and fast rule which can be used to determine exactly what results will be obtained with each element and each cathode. Both electroplating and electrodeposition are greatly influenced by the character of the cathode surface, as well as by the composition of the electrolysis solution. Cathodes of the same material will vary from lot to lot, and even from front to back. For these reasons, duplicate determinations will frequently produce films greatly different in appearance, and possibly in composition or crystal structure. Presumably identical electrolysis solutions and cathodes will frequently show wide variation in gas production, even though the currents and anode potentials are the same.

The formation of satisfactory films by electrodeposition is more critically influenced by the character of the cathode surface and solution

composition than is such formation by electroplating. The greatest problem in electrodeposition is to obtain a film which will adhere to the electrode and it is for this reason that etching of the surface may be advantageous. Inasmuch as no definite instructions can be given in every case regarding the selection of a satisfactory cathode, it is often necessary to try each metal in turn, starting with platinum or copper.

Since the cathode surface is so important to satisfactory film formation, thorough cleaning of discs can not be over emphasized. Surface impurities result from rolling, handling, dust, oxidation, and attack by moist air containing small amounts of such gasses as  $\text{SO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{HCl}$ ,  $\text{HNO}_3$ , etc., which are not usually excluded from the air in the laboratory.

The greasy coating due to handling should be removed before the oxide and salt coating, unless removal of both can be accomplished together. The noble metals, gold and platinum, are readily cleaned by immersion in warm concentrated sulfuric acid-dichromate cleaning solution, and if desired, this treatment may be followed by boiling in either concentrated nitric or hydrochloric acid.

Copper and iron may be degreased with organic solvents, or by immersing for a very short period in the dichromate cleaning solution, followed by washing with hot water, or they may be cleaned with fine sand paper. After any of these procedures, immersing in cold dilute hydrochloric or nitric acid will complete the cleaning. Nitric acid will attack and etch the copper surface faster than hydrochloric, while the reverse is true with iron, and advantage may be taken of these rate differences to effect cleaning with or without appreciable etching. As pointed out above, it may sometimes be advantageous to etch the cathode during cleaning, using aqua regia or

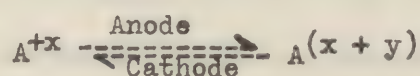


sandblasting if necessary. Rinsing of discs in acetone before drying is particularly recommended for cathodes which are easily oxidized.

### F. Electrodeposition

The electrodeposition process involves not one, but two different chemical reactions; namely, oxidation or reduction, and concurrently, precipitation of an insoluble salt on the electrode. Electrodeposition, unlike electroplating, can occur on either the anode or the cathode. Anodic depositions, although reported in the literature, have not, as yet been successfully applied to the problems of radiometry. Anodic films of lead sulfate and oxide, and of manganese oxides, for example, have been produced, but procedures for quantitative recovery, by this means, have not been worked out.

The underlying principle upon which electrodeposition is based can be explained as follows: A cation, A, which can exist in solution in either of two or more valence states, is oxidized at the anode and reduced at the cathode. An anion, B, also in solution, but neither electrolytically oxidizable or reducible, forms an insoluble compound either with the reduced cation but not the oxidized, or with the oxidized but not the reduced. If the reduced cation deposits with B, then cathodic deposition is obtained, and by the converse process, anodic deposition may be obtained. These reactions may be represented as follows:



are the cation electrode reactions, where x has a value between 1 and 3, and the quantity (x + y) has a value between 2 and 5. If the anion B has a valence of -z, it will form two salts with A; namely,  $A_zB_x$  and  $A_zB_{(x+y)}$ . For electrode film formation, one of these must be insoluble in the electrolysis solution. Of necessity, the cation must be introduced into the electrolysis solution in such a valence state that it will not form this precipitate in the

solution itself.

Neglecting valences and electrolysis reactions for the moment, one other consideration is important; namely, the independent role which B plays in forming and maintaining the precipitated film. The reaction which occurs may be represented as:



The equilibrium constant for this reaction,  $K_{ab}$ , equals the product of the concentrations of A and B; the value of each of the latter is squared or cubed, etc., depending upon whether 1 or 2, etc., ions are concerned in forming the precipitated molecule. Therefore, the greater the concentration of B in solution, the smaller will be the concentration of A when equilibrium is reached, and thus, the more quantitative the recovery.

The electrodeposited film, however, is not only slightly soluble in water, but is usually dissolved by acid or base, or by complex ion formation. If the rate of solution by any one or combination of these reactions is faster than the rate of valence change and precipitation, no electrode film will form. A rather delicate balance of these reaction rates is usually necessary if quantitative results are to be achieved and such side reactions must be eliminated or minimized.

#### G. The Electrolysis Current and Voltage

A convenient power supply for electrochemical reactions is the ordinary 6 volt storage battery. Voltages above 12 are not usually necessary, and a parallel, or series-parallel arrangement of two or four batteries will supply as much power as will, in general, be needed for routine analytical work. Electrolyses from non-aqueous solution, however, may require much higher voltages, in which case a vacuum tube d.c. power supply will be much



more convenient than either batteries or a generator.

Means are generally provided, in the electrical circuit, for some type of voltage, and consequently, current, control. When the power is supplied by storage batteries, voltages may be varied by selecting the number of cells. Intermediate voltage control can then be accomplished by using a suitable variable resistance, which is connected in series with the electrolysis cell.

In addition to voltage regulation, three additional independent variables will influence the electrolysis current; namely, the distance between anode and cathode, the resistance of the electrolysis solution, and the electrode-solution boundary resistances. The electrolysis solution resistance, in turn, is dependent upon the ion concentration and upon the temperature of the solution; increasing either one decreases the resistance.

The desired electrochemical reactions occur only at the boundaries joining the electrodes and the electrolysis solution; therefore the potential drop across each of these boundaries is of considerable importance. These electrode voltage drops determine which reactions will occur, and the current which flows determines the reaction rates. If either of the boundary resistances or that of the solution, is too high, little or no current will pass through the cell, and, consequently, the reaction rates will be negligible.

The minimum electrode reaction potentials are determined by first, the back e.m.f., which is the potential with which the particular reactions tend to reverse themselves, second, the "passivity" of the electrodes, and, third, the "polarization" within the boundary. The last named phenomenon results, primarily, from localized concentration changes of the electro-

sis solution; passivity is due to electrode surface conditions for which discussions will be found in standard texts. An electrode becomes polarized due to the progressive removal of one or more ions, by reduction or oxidation, within the boundary; equilibrium is regained or maintained by rapid stirring of the solution. The net result of the above three factors is to establish a minimum potential below which little or no current will flow and no reactions will occur, and above which a rapid increase in current is obtained.

The polarization of an electrode, which is required to produce a given irreversible reaction under given conditions, is known as the overvoltage of this reaction. Overvoltage values for the same reaction vary considerably, depending upon the electrode material and surface condition. Thus the hydrogen overvoltage for a platinized-platinum cathode is lower than for smooth platinum, which, in turn, is lower than for mercury, and so forth.

The importance of hydrogen production at the cathode may be illustrated by the following example: if the electrode e.m.f. for the reaction or reduction of A is 0.5 volt, and the hydrogen overvoltage is 1.0 volt, reaction A will begin when the potential slightly exceeds 0.5 volt, and will continue with little or no hydrogen evolution until the potential reaches 1.0 volts. At this point hydrogen gas begins to form, and as the voltage increases, both hydrogen formation and reduction of A occur together. The reduction of hydrogen at the cathode is accompanied by the formation of hydroxyl ions. These, in turn, may exercise considerable influence on the reduction of A, or upon the character of the reduced film. If this influence is deleterious, then voltages below the hydrogen overvoltage



should be employed. On the other hand, increased alkalinity may be helpful; furthermore, the presence of hydrogen gas within the body of the solution may cause reductions which will aid in the quantitative recovery of A.

When the hydrogen overvoltage is much lower than the voltage necessary for the reaction A and the applied voltage is between the two, then no reduction of A will occur, and only hydrogen gas will be formed. To overcome this, a different cathode material with a higher overvoltage may be used, or, the voltage may be increased to the point where reaction A begins to occur, whereupon the cathode becomes coated, and the hydrogen overvoltage increases to a value which is characteristic of a cathode made of metal A. Of course, if the hydrogen overvoltage of the latter metal is lower than the voltage necessary for its plating, then the reduction rate may be very slow, and may not occur quantitatively within a finite time.

Oxygen overvoltages, and the formation or lack of formation of oxygen gas and hydrogen ions, should be considered in exactly the same relation, but with respect to the anode. However, since most of the electrolysis work with radioactive materials will be concerned with cathodic film formation, anodes with low oxygen overvoltages should be employed; this condition is adequately met with in platinum.

The following procedures are quoted practically verbatim from the work of Hahn (1):

A. Electroplating

"The iron or tissue sample has added to it enough ordinary iron in the form of ferric chloride to make the estimated total iron about 5 to 10 mg. In the case of tissues or samples containing organic material or iron in the form of some complex, the sample is first wet-ashed. With phenolsulfonphthalein as an indicator, the digest is brought nearly to neutrality with 40% sodium hydroxide and transferred to one or more 50-ml. centrifuge tubes. More sodium hydroxide is then added until it is well over the alkaline end point and the iron hydroxide is allowed to precipitate overnight. Following centrifuging, the supernatant liquid is decanted and the precipitate is dissolved in a few drops of concentrated hydrochloric acid. Usually it is advisable to reprecipitate once to remove excess ammonium sulfate which is entrained. After being heated nearly to dryness to remove the excess hydrochloric acid the sample is transferred to the electroplating cell."

"Fifty milligrams of cevitamic acid are added, followed by 8 drops of 28% ammonia solution. Two milliliters of a saturated solution of sodium citrate are added, making a total volume of 20 to 25 ml. The material is plated out at an e.m.f. of 6 volts and a current of 300 milliamperes at the start. As plating proceeds the current is allowed to increase spontaneously to 350 to 400 milliamperes. The complex formed by the mixture of these reagents is soluble and allows the plating to proceed in alkaline solution, resulting in a smooth, even, shiny plate."

"In many instances plating was complete in 2 hours or less, but it was



felt advantageous to allow 3 hours to ensure a negative test for iron in the electrolyte. At first the electrolyte is a deep brown color, which gradually lightens until it is almost colorless when electrolysis is complete. The electrolyte can easily be tested for the presence of residual iron by a semi-quantitative use of the thiocyanate test. After acidifying the electrolyte with a few drops of concentrated hydrochloric acid, a few drops of a solution of (50%) ammonium thiocyanate are added and the intensity of color is noted. Following a good plating operation the reaction is either negative or indicates the presence of from 0.01 to 0.05 mg. of iron. This amount corresponds to deposition of over 99% of the iron. When plating is completed the cevitic acid has presumably been entirely used up and there has been sufficient anodic oxidation to make it unnecessary to modify the test further to obtain an adequate reaction with ferric iron. At the beginning of a typical electroplating run the pH of the electrolyte was found to be 8.8 and at the end it was 8.3.

"This procedure is obviously a highly empirical and electrically inefficient one. However, it has given excellent results in the authors' hands and as many as 100 shiny, evenly distributed plates have been obtained consecutively without a positive analysis for residual iron."

In carrying out Hahn's method, it will probably be found more convenient to add the cevitic acid in solution. For this purpose, a freshly prepared 5% solution in 0.01 N HCl will be satisfactory. Since cevitic acid undergoes a reversible oxidation below pH 4.0 and an irreversible one in more dilute acid or in alkaline solution (2), it is recommended that 1 ml. of this reductant be added as directed, and again after one and after two hours, thus insuring the presence of a sufficient amount of the reagent at all times. This same reagent solution may also be used in the analytical

procedure, below.

In the presence of citric acid, the thiocyanate test for ferric iron may be negative, due to the formation of a ferric citrate complex (3). Furthermore, successive additions of cevitamic acid may reduce nearly all the iron to the ferrous state. In testing the electrolysis solution for residual iron, therefore, it will probably be better to remove an aliquot, reduce with hydroxylamine in hydrochloric acid solution, and then to apply the  $\alpha, \alpha$ -dipyridyl test (4). Acidifying the electrolyte in the cell etc., in order to make the thiocyanate test as outlined by Hahn may give erroneous results, due to the dissolution of some iron from the cathode by the hydrochloric acid.

#### B. Iron Analysis

"The method for determining total iron is a simple modification of the  $\alpha, \alpha$ -dipyridyl reaction described by Hill."

"An iron standard is made from Mohr's salt or iron wire, such that it contains 1.00 mg. of iron per ml. of solution. From this a dilute standard which contains 0.01 or 0.05 mg. of iron per ml. is prepared at intervals."

"An aliquot of the unknown material estimated to contain approximately 0.1 mg. of iron, and the dilute standard, are run simultaneously in 25 ml. volumetric flasks. A pinch of cevitamic acid is added to each to reduce the iron to the ferrous form and 15 ml. of a sodium acetate-acetic acid buffer solution (pH 5.4) are added. One milliliter of a 0.2% solution of  $\alpha, \alpha$ -dipyridyl solution in 10% acetic acid is added and the sample is diluted to volume with distilled water. After mixing and allowing to stand at room temperature for 0.5 hour the colors are read in a Klett-Summerson photo-electric colorimeter using a Klett No. 54 (500 to 560 m $\mu$ ) filter."

"When tissues are to be analyzed, the amount of material taken is



such that it contains an estimated 0.5 mg. of iron, which is enough for several determinations. Wet-ashing with concentrated sulfuric acid and 60% perchloric acid is carried out as described elsewhere. After being diluted to a known volume, an aliquot is titrated against strong ammonium hydroxide, using methyl red as an indicator. This same amount of ammonium hydroxide is then added to an aliquot to be used for the iron determination and the procedure as outlined above is followed. If the colorimetric reading is  $\pm 20\%$  of the reading of the standard the determination is repeated, using a larger or smaller aliquot of the ashed material with a corresponding amount of ammonium hydroxide. The method is rapid and simple and has given good results with a moderate amount of practice."

If Mohr's salt (ferrous ammonium sulfate) is used to prepare the standard iron solution, sufficient acid must be added to prevent hydrolysis. Oxidation of the iron by atmospheric oxygen can not be prevented by the addition of acid, however, so that upon standing both ferrous and ferric iron will be present. The tendency of the latter to hydrolyze is greater than the former, but if sufficient acid, preferably hydrochloric, was originally added to the ferrous solution, no precipitation of basic ferric salts should occur, and the standard solution may therefore remain clear indefinitely. Under other conditions it will become opalescent after standing for some weeks.

The procedure for gold reported by Dunn (5) is outlined below. It has been successfully used for several months in the Division of Medical Physics, University of California. Inasmuch as the chemistry involved is uncomplicated by interfering side-reactions, the procedure is relatively simple and rapid.

#### A. Procedure

The weighed tissues are digested in 25 ml. Erlenmeyer flasks, using either aqua regia, or concentrated nitric acid plus superoxol. In either case, only small amounts of reagent are added at one time. If excessive frothing is encountered, one drop of octyl alcohol is added. Complete oxidation of the latter, as well as the tissue, must be accomplished before proceeding further.

As a carrier, 2.0 ml. of a reagent grade gold chloride solution may be added either before, during, or after digestion, although addition at an early stage in the digestion is recommended. The concentration of this solution should be accurately known, and the solution should contain approximately 5 mg/ml. of metallic gold, as the chloride. The concentration of gold in the carrier solution is determined either by electrodeposition on tared platinum discs, or by evaporating a known volume to dryness in a tared porcelain crucible, followed by heating to decompose the chloride, cooling, and weighing.

Upon completion of digestion, excess nitric acid is removed by adding successive small amounts of concentrated HCl, with heating. The resulting solution is evaporated to 1-2 ml. and transferred to a 15 ml. centrifuge cone. Only a roughly quantitative transfer is needed, since the electro-



deposited film is to be weighed, and recoveries as low as 90, or even 80%, are acceptable.

The separation of the gold from all or nearly all of the associated elements in the tissue digest is accomplished by reducing the gold to the metallic state. The reducing solution is made up to contain approximately 10%  $\text{NH}_2\text{OH}\cdot\text{HCl}$  and 0.4%  $\text{FeSO}_4\cdot 7\text{H}_2\text{O}$ . Two ml. of a freshly prepared solution are used for each 10 mg., or less, of metallic gold. Reduction is hastened by placing the cones in a beaker of hot water which is kept just below the boiling point for 15 - 30 min. The ferrous sulphate is omitted from the reducing solution when urine and feces samples are to be run.

After centrifuging, the supernatant liquid is discarded. The centrifuge cone wall and the gold may be washed, followed by centrifuging, and the wash solution also discarded.

The pellet of precipitated gold is readily dissolved in a mixture of 4 drops of hydrochloric acid plus one drop of nitric. Placing the cone in a beaker of hot water accelerates the reaction, which is usually complete within 15 minutes. The aqua regia solution of gold is made alkaline with 5 ml. of 1 N sodium hydroxide. After mixing, this solution is transferred to the electrodeposition cell. The latter should be assembled using a tared and numbered disc and should have 2 ml. of a 5% solution of potassium cyanide in 0.1 N sodium hydroxide, covering the disc before the gold solution is added. The centrifuge cone is washed with distilled water which is also poured into the cell. In routine work this washing is accomplished by filling the cone once with distilled water, followed by transfer to the cell.

The anode is placed in the solution at about 3/4" to 1" from the

cathode. The current is adjusted to approximately 85 ma. Since the actual plating area is about 8.5 sq. cm., the current density will be 10 ma/sq. cm., or approximately twice the current recommended for commercial electroplating. Deposition is allowed to proceed for one hour at room temperature. At the end of this time an additional 2 ml. of the cyanide solution are added, followed by another hour of electrodeposition.

Upon removal of the anode, the cell contents are discarded, and the cell is washed with distilled water. After disassembly, the disc is again washed, rinsed in acetone, and placed in a warm place to dry. The gross weight is generally obtained before the radioactivity is determined, although this is not essential.

#### B. Notes on the analytical procedure

1. Digestion. As often happens in the wet digestion of biological tissues, there are occasional samples which precipitate difficultly soluble crystalline salts upon evaporation to small volume. When this occurs, the solution and precipitate are transferred together to the centrifuge cone, and the procedure carried through as with the other samples. The presence of this material, which is always in very small amounts, apparently does not interfere with the results. To insure that no radioactive gold is lost, however, any insoluble material should be dissolved at some point between the time the carrier is added and the time reduction is completed, even though an extraneous precipitate appears later, as it frequently does with urine and feces samples. This precipitate does not interfere with the electrodeposition. When octyl alcohol is used to prevent frothing, a waxy material is frequently formed which has a low melting point, and which may not be observed until the solution is cooled to below



room temperature. Precautions should be taken to obtain complete digestion of this organic matter.

2. Reduction. Either hydroxylamine or ferrous sulphate may be used to reduce the gold. Ferrous sulphate reduces the gold more rapidly than the hydroxylamine, but gives a precipitate which dissolves less rapidly in aqua regia. When using ferrous sulphate, there is usually a small amount of unwetted gold floating on the meniscus after centrifuging. This gold is either lost upon decantation, or must be removed on a stirring rod, and returned later. Reduction with hydroxylamine occurs in three distinct phases; namely, reduction to aurous, formation of colloidal gold, and finally, precipitation of the metal. Unwetted gold is not usually obtained when this reagent is employed but the formation of a light "gold mirror" is frequently observed. When a mixture of both reductants is used, both phenomena are less pronounced, and the rate of reduction is about the same as with ferrous sulphate alone.

3. Solution of gold in aqua regia. When mirror formation is encountered, the cone is placed in only about 1" of hot water to hasten the dissolving reaction. Sufficient acid condenses on the wall of the cone to dissolve the mirror completely.

4. Addition of NaOH. If insoluble salts are present after digestion, a white precipitate is sometimes present, or is formed, at this point. If desired, this insoluble material may be removed by centrifuging before the solution is transferred to the electrodeposition cell.

5. The cathode disc. Both platinum and gold-plated copper discs may be cleaned by immersing in warm concentrated sulphuric acid-dichromate cleaning solution. With the latter type of disc, immersion should not be longer than 2 to 3 minutes, since the plate does not offer sufficient protec-

tion to the copper to prevent its dissolving. Both types of disc must be thoroughly rinsed after this treatment. The platinum discs may be dried directly after washing, but an acetone rinse is first recommended for the gold-plated copper. Heating the platinum discs over a burner, in order to dry them, is not recommended, since they then lose their temper, and are more difficult to handle without bending. Experiments carried out by Bertrand (6), indicated that plain copper discs lose rather than gain weight during electrodeposition. Gold-plated copper discs are therefore used in order to minimize the formation of oxide film on the surface of the copper, and attack of the copper by the cyanide plating solution. The alternatives are to use either gold or platinum discs, which, in view of the number needed, and the difficulties involved in removing the radioactive layer, will generally not be economical. While the use of plated copper does not entirely eliminate the weighing error, the results obtained are satisfactory for this type of analysis. The actual plating may be done on strips of copper  $14'' \times 1\frac{3}{4}'' \times 0.002''$ . The  $1\frac{1}{2}''$  diameter discs can then be punched out.

6. Electrodeposition. The plated discs in the assembled cells frequently discolor upon transferring the gold solutions to them. This occurrence is minimized, but not entirely eliminated, by adding the cyanide solution to either the cone or the electrodeposition cells before transferring. The addition of the KCN directly to the cone prevents precipitation of auric hydroxide; the latter sometimes occurs upon allowing the solution to stand for several hours with NaOH alone. The color of the gold plate on platinum discs is either yellow or light orange, while that on gold-plated copper varies from light rose to brown. Gold plates on platinum frequently show small blisters in which case the deposit is easily broken loose upon scratching. Blistering, however, does not occur with the plated copper discs, but



the deposit on these discs can be rubbed off to an appreciable extent, perhaps due to the admixture of copper; highly active discs must be handled carefully in order to prevent contamination of counters, etc., due to powdering off of small, unweighable amounts of gold.

## 28. THE ELECTRODEPOSITION OF URANIUM

Several methods have been developed for the electrodeposition of  $\text{UO}_2$  and  $\text{UF}_4$ , but, as of the date of this writing, only two declassified documents on this subject have come to the attention of the writer. The procedures quoted in these declassified papers were developed independently by Hull (7) and by Kahn and Dunn (8). The former author deposited the oxide from a warm oxalate solution and the latter the fluoride from dilute sodium fluoride at room temperature.

Procedures for the separation of uranium from tissue ash have been developed but not published. The electrodeposition technic outlined below presupposes that a nearly pure sample of  $\text{U}_3\text{O}_8$  is available as the starting material. The details of this procedure are taken from a report by Lilly, using the fluoride method (9).

Preparation of Sample. Estimate the weight of the sample and weigh the  $\text{U}_3\text{O}_8$  on a balance which is sensitive enough to give an accuracy of not less than 99.5% in the weight of oxide.

Solution in Nitric Acid after Ignition. Try to dissolve the sample by using less than fifteen drops of concentrated nitric acid per 100 mg. of uranium. Use as little acid as possible in each case. If the sample dissolves completely, it may be centrifuged and made up to volume, and the aliquot may be pipetted directly into the electrodeposition cell for plating. If the sample does not dissolve, more nitric acid must be added. After centrifuging and making up to volume, it is then necessary to evaporate the nitric acid from the aliquot in a small beaker. Samples containing less than 30 mg. of uranium will generally require more than the tolerable amount of nitric acid and should be handled as directed above.



Measuring Out the Aliquot. Choose the Normax flask and pipette combination which will give a disc deposit weighing as close to 500 gamma as possible.

Evaporation of Nitric Acid from the Aliquot when Necessary. If more than the maximum amount of nitric acid has been added, pipette the aliquot into a 5 or 10 ml. beaker and place on a low hot plate under an air jet. Evaporate the sample to complete dryness. Add a few drops of water to the warm beaker; if no nitric acid odor can be detected, add more water, heat gently, and pipette into the electrodeposition cell. If there is still acid present, take to dryness again. Repeat until there is no odor on the addition of water to the warm sample. In case the sample does not re-dissolve in water, add one drop of 0.5 N nitric acid solution. This should be adequate; in any case, do not add more than two drops of this solution to any one aliquot. The sample may then be pipetted into the electrodeposition cell.

After pipetting the sample into the electrodeposition cell, add 5-10 drops of nitric acid to the small beaker in which evaporation was carried out. Make up to about 5 ml. and test for residual uranium using a fused sodium fluoride bead, as outlined below. The results of this bead test should insure that the uranium was transferred quantitatively to the cell.

Plating Procedure. Pipette the sample into the cell, keeping the volume down to about 10 ml. Add 2 ml of 1% sodium fluoride, and adjust the stirrer so that it is about 1/4 in. above the surface of the disc. Run at 50 ma. Add an additional 1 ml of 1% sodium fluoride after one hour. At the end of 1-1/2 hrs., stop the stirrer and dip a fused sodium fluoride bead into the solution. Fluorescence of this bead should show that less than 3 gamma of uranium remains unplated. When these conditions are satisfied, the disc can be removed and ignited.

If too much uranium remains unplated, add an additional 1 ml. of 1% sodium fluoride and run for half an hour before testing again. If the amount of uranium remaining after two hours is more than 1% of the total, a new plate should be started.

In the presence of very slight excess amounts of nitrate, chloride, and sulphate, the electrodeposition is either incomplete, or does not occur at all. Very little work has been done to determine the side reactions which occur, or how to minimize them.

Flourescent Bead Test. Fused beads of NaF are prepared by the method of Zebroski and Newton (10). 3 mm. i.d. loops of 0.020" or 0.030" platinum wire are heated and dipped into powdered NaF. The powder adhering to the loops is then fused into a bead. Before use, background fluorescence must be checked on each bead. If there is little or no detectible difference between the fluorescence of a blank bead, and one which has been dipped in a solution containing 1/4 microgram per ml. of uranium, the NaF should be repurified.

Ultraviolet light from a Mazda CH-4 lamp is convenient for this fluorescence analysis. The light is passed through a Corning No. 586 or 587 filter, and the bead is viewed through a Wratten G filter. With this set-up as little as 1/8 microgram per ml. of uranium is detectible.

The apparent fluorescence of uranium is decreased about 10% when from 0.04 to 0.6 micrograms per bead of interfering elements are present, depending upon the elements. Among those elements which quench the fluorescence in this concentration range, are Cr, Mn, Fe, Co, Ni, Sb, Pb, and Ag. A detailed discussion of interference is given in the above-mentioned report.

Standard beads may be prepared for semi-quantitative analysis using solutions containing 1/8, 1/4, 1/2, 1, 2, 5, and 10 micrograms of uranium per ml. The fluorescence of both blank and standard beads increases with time. Reference beads should therefore be prepared only as needed.



## References

1. Hahn, P. F., Ind. Eng. Chem., Anal. Ed. 17, 45 (1945)
2. Bodansky, Meyer. "Introduction to Physiological Chemistry" p. 304,  
New York, John Wiley and Sons, 4th Ed. 1938.
3. Feigl, F. "Qualitative Analysis by Spot Tests", p. 212, New York,  
Elsevier Publishing Co., Inc. 3rd Ed. 1946.
4. Ibid. p. 122.
5. Dunn, Rayburn W. "Recovery and Estimation of Radioactive Isotopes from  
Biological Tissues. I Gold. (to be published)
6. Bertrand, J. J., Private communication.
7. Hull, D. E. "The Counting Method of Isotopic Analysis of Uranium". Jan.  
1944. Manhattan Project Series. M.D.D.C. 387
8. Kahn, Milton, and Dunn, R. W. Univ. of Calif. Rad. Lab. Special Report  
No. 24, 1943 (Classified)
9. Lilly, R. C., "A non-gravimetric method for the determination of uranium  
on platinum discs" 1945. Manhattan Project Series M. D. D. C.
10. Zebroski, E., and Newton, T. W. "Fluorescence Analysis for Uranium"  
Manhattan Project Series 1944. M. D. D. C. 443
11. Hawk, Philip B., Oser, Bernard L., and Summerson, William H., "Practical  
Physiological Chemistry" p. 987. Philadelphia. The Blakiston Co.,  
12th Ed., 1947
12. Ibid., p. 451
13. Association of Official Agricultural Chemists, "Methods of Analysis"  
p. 237, Washington, D. C. Association of Official Agricultural  
Chemists, 6th Ed. 1945
14. Ibid., p. 238
15. Smith, G. Frederick, "Mixed Perchloric, Sulfuric and Phosphoric Acids and  
Their Application in Analysis. Columbus, O. G. Frederick Smith  
Chemical Co. 2nd Ed. 1942

16. Kahane, Ernest "L'Action de l'Acide Perchlorique sur les Matieres  
Organique. I and II." Paris, France, Herman et Cie., 1934



Radioautography is a technique utilizing the photographic effect of ionizing radiations by which the distribution of radioactive materials in tissues may be shown. A sample of material containing the radioactive isotope in tracer quantities is placed in close contact with a photographic film. Where particles from the sample have passed through the emulsion, the film will be blackened and by comparison of the developed film and the sample it is possible to determine the distribution of the isotope in the sample. A method was first reported by London (1) in 1904 and subsequently by Kotzareff (2) in 1922; both used it to investigate the distribution of radium. Up to the present, a number of papers have been presented which describe modifications and refinements of the method developed by these investigators. Excellent reviews of the subject have been given by Gross and LeBlond (3) and by Axlerod (4).

Using this technique, the distribution of numerous elements have been studied in many different tissues. Among these are Ra, Po, Pb, and P in body tissues; Pb, P, Sr, Pu, Y, Ce, and C in bone; I in thyroid; and P and C in plant tissues.

In the procedure first mentioned, a block of tissue is placed on a photographic plate, with cellophane interposed when necessary, to protect the plate from moisture. Relatively close contact is maintained by firmly clamping the specimen and plate together during exposure. A general idea of gross distribution can be obtained in this way but the resolution is poor because of the effects of scattering and absorption of particles emitted from different portions of a thick specimen.

Better definition has been secured by improvements in the technique developed mainly through the use of histological sections rather than thick

specimens and thus avoiding excessive scattering and absorption. Contact between the section and plate may be made by one of the following methods:

1. Placing a section on a slide and then clamping the slide to the film with the section next to the emulsion.
2. Floating sections, still in the embedding medium, onto film.
3. Covering sections with liquid emulsion or stripping film.

The first procedure is probably the simplest. Normal histological techniques may be used in preparation of the slide providing the precautions discussed below are heeded. The film and section are held in contact in a suitable frame and stored in a light tight container. After a sufficient time has elapsed, the autograph is developed and the section stained. Subsequent comparison of the picture and the section will then reveal areas of concentration of radioactive substances. In some instances however, precise localization of the material under observation is not possible because of the difficulty of exact realignment of section and autograph. For example, the question of whether iodine in the thyroid is located in the follicular colloid or epithelium is not readily answered unless exact alignment of autograph and section can be made.

The other methods involving tissue sections eliminate this difficulty. In the second method, the section is floated onto the film and after a suitable exposure time in the dark, the embedding material is removed, the autograph developed with the section still in place and the section then stained. Although localization of the material is good in this case, a stain which will not be more strongly absorbed by the emulsion than by the tissue must be used. In some instances, this may result in poor histological differentiation.

The problem of staining the tissues is not encountered in the third method. In addition, it offers the advantage that the scattering of radio-



active particles is still further diminished since no film backing is present. Here, the sections are first stained and then coated with a very thin film of celloidin. The emulsion is placed over the section either by painting on the liquid or by dementing on "stripping film", a recently developed preparation in which the film may be removed from its backing. The liquid emulsion may be secured commercially or scrapped from ordinary film and melted. It is difficult to spread the liquid emulsion to form a layer of even thickness and the necessary manipulations may cause an increased graininess. The use of stripping film avoids these problems and has been highly successful in some cases (5). Other workers (6) however, have found it necessary to use excessive care to keep the film on the slide and to prevent swelling of the emulsion during development.

Several factors are important to securing good radioautographs by any of the methods listed above. All solutions used in preparing the tissues, such as fixatives, dehydrating agents, and stains should be tested to insure that the radioactive material is not leached from the tissue before the autograph is made. For careful work, it is advisable to secure autographs by two different methods to eliminate the possibility of shifting of the material in the tissue during manipulation. The exposure time and, to some extent, the sharpness of the autograph, depend on the radiation used and the overall and local concentration of the material in the sample. Alpha and soft beta emitters give excellent autographs since the short range allows complete absorption in the emulsion. With beta particles of higher energy and longer range, the autograph will tend to be more diffuse. No radioautographs obtained with pure gamma emitters have been reported. It is usually necessary, in the final analysis, to determine the exposure time for a sample by experiment. However, counting the sample prior to exposure frequently will indicate

a reasonable time period. A total of approximately 10 million beta particles and 2 million alpha particles per square centimeter generally are necessary. With track autographs, which are possible only in the case of alpha emitters, the number of particles necessary is much less since the individual tracks rather than the film blackening are to be observed. If all the material is localized in a few small areas in the tissue section, fewer disintegrations per square centimeter will be necessary.

The choice of film to be used will be governed by the particle emitted. High speed and fine grain are very desirable. The former characteristic is essential for work with short-lived isotopes. With beta emitters, and alpha emitters when track autographs are not desired, satisfactory autographs may be obtained with Eastman "No-Screen", Ansco "non-Screen", dental X-ray film, and lantern slide plates. The last mentioned are not satisfactory for small amounts of activity since they have a relatively slow speed emulsion. For alpha track autography, special emulsions have been developed by Eastman and Ilford.

The resolution of the picture obtained will depend on a number of factors in addition to the type of particle studied and film used. Briefly, these are: thickness of the section studied; contact maintained between sample and film; scattering of radiation; and exposure time. Although the presence of radioactivity may be demonstrated with thick samples, a rather diffuse picture will be obtained. The closer the contact between film and sample, the better will be the resolution but the pressure used during exposure must be even and constant to avoid blurring of the image. If it is necessary to interpose cellophane between the sample and the film to protect the latter from moist tissues, resolution will, of course, be diminished and it will be impossible to obtain autographs with alpha and very soft beta emitters because of absorption of these radiations. With thin samples, 5 u



or less, scattering of radiation by the tissue is negligible, but backscattering from the film backing will be troublesome especially with energetic beta particles. This is, of course, eliminated by the use of liquid emulsion or stripping film. Over-exposure will also cause diffusion of the image, and thus diminish resolution.

Details of the various procedures described above may be obtained from Axelrod (4)(all methods), Evans (7), or Endicott and Yagoda (8) (sections floated on film), and Belanger and LeBlond (9) or Demmer (10) (liquid emulsion spread on samples.)

#### REFERENCES

1. London, E. S., Arch. d'Elect. Med. et de Physiotherap. du Cancer, 12, 363 (1904).
2. Kotzareff, A., Jour de Radiol. et d'Elect., 6, 631 (1922).
3. Gross, J., and LeBlond, C. P., McGill Medical Jour. 15, 1 (1946).
4. Axelrod, D., USAEC at U. of C. BP-111.
5. Gray, L. H., Personal communication.
6. Axelrod, D., Personal communication.
7. Evans, T. C., Proc. Soc. Exp. Biol. Med., 64, 313 (1947).
8. Endicott, K. M., and Yagoda, H., Proc. Soc. Exp. Biol. Med. 64, 170 (1947).
9. Belanger, L. F., LeBlond, C. P., Endocrinology, 39, 8 (1946).
10. Demmers, P., et al., Can. J. Res. Sect. A. 25, 223 (1947).

## 30 INSTRUMENT MANUFACTURERS

### A. Counting Equipment

#### ATOMIC INSTRUMENT COMPANY

158 Charles Street  
Boston 14, Massachusetts

1. Radioactivity demonstrator
2. Linear amplifier (Model 204)

#### BERKELEY SCIENTIFIC COMPANY

601 Nevin Avenue  
Richmond, California

1. Counter, scale of 64

#### CYCLOTRON SPECIALTIES COMPANY

Station D, Morago, California

1. Impulse register
2. Counter
3. Mica window Geiger tube

#### ECK AND KREBS

131 West 24th Street  
New York, N. Y.

1. Geiger tubes

#### FRED C. HENSON CO.

Pasadena, California

1. Quartz fiber electroscope

#### HERBACH AND RADMAN COMPANY

517 Ludlow Street  
Philadelphia, Pennsylvania

1. Counter, scale of 32 (Model GL 532 C)
2. Counting rate meter and counter (Model GRM-471)

#### INSTRUMENT DEVELOPMENT LABORATORIES

817 East 55th Street  
Chicago 15, Illinois

1. Counting circuit, scale of 64 (model 161)
2. Portable counting rate meter (model 2610)
3. Landsverk electrometers
4. Counting tubes for gamma and beta radiation
5. Accessary equipment



NORTH AMERICAN PHILIPS COMPANY, INC.

Dept. X-6  
100 East 42nd Street  
New York, N. Y.

1. Portable radiation detector
2. Geiger-Mueller counters

POTTER INSTRUMENT COMPANY

136 - 56 Roosevelt Avenue  
Flushing, New York

1. Dual-predetermined Electronic counter
2. Counter chronograph interval timer
3. Two-decade electronic counter
4. Preset internal timer

RADIATION COUNTER LABORATORIES

1451 East Fifty-seventh Street  
Chicago 37, Illinois

1. Geiger-Muller counters

SYLVANIA ELECTRIC COMPANY

Electronics Division  
500 Fifth Avenue  
New York City, N. Y.

1. Geiger-Muller counters

TECHNICAL ASSOCIATES

3730 San Fernando Road  
Glendale, California

1. Geiger tubes

TRACERLAB, INC.

55 Oliver Street  
Boston, Massachusetts

1. Autoclaver
2. Beta and gamma standards

VICTOREEN INSTRUMENT COMPANY

5806 Hough Avenue  
Cleveland, Ohio

1. Geiger tubes
2. Portable counters

## B. Mass Spectroscopes

BERKELEY SCIENTIFIC COMPANY  
601 Nevin Avenue  
Richmond, California

CONSOLIDATED ENGINEERING CORPORATION  
Pasadena 4, California

1. Mass spectrometer
2. Electrical computer (Model 30-103)

DISTILLATION PRODUCTS, INC.  
Vacuum Equipment Division  
Rochester 13, New York

GENERAL ELECTRIC  
Special Products Division  
Apparatus Department  
General Electric Company  
Schenectady 5, New York

1. Mass spectrometer
2. Time internal meter
3. Nuclear research equipment



### III. BIOLOGICAL AND MEDICAL APPLICATION OF ISOTOPES

#### 31. INTRODUCTION

The object of this division - Part III - of the handbook is to supply a critique and discussion of the significance of stable and radioactive isotopes in biology and medicine. The succeeding parts (nos. 32-38) of Part III consist of 1, a section (no. 32) in which is presented a general critique of the biological and medical applications of isotopes; 2, several sections (nos. 33-36) in which the elements, arranged generally according to their biological significance, are considered; 3, a section (no. 37) on isotopes in medical therapy and diagnosis; and 4, a section (no. 38) on the biological effects of the natural radioactive elements. In each section representative works are cited from the regularly published literature that illustrate the main types of problems that have been studied.

A bibliography of all publications dealing with stable and artificial radioactive isotopes as tracers and with the effects and differential behavior of isotopes in biological systems is to be found in Part IV; papers describing chemical syntheses or physical measurements have not been included unless they also give data on biological application. Section 38, having been prepared separately (by Dr. P. P. Weymouth) and dealing with the natural radioactive isotopes, has a separate list of references appended directly thereto. In Part IV there is an introductory list of general references (Gen); otherwise the references are grouped according to element, which are listed alphabetically. Under each element references are in turn listed alphabetically according to author, and each is assigned the symbol of its element and a serial number. In sections 32-37 citations are made by use of these designations (e.g.; Nall, S6, etc.). The bibliographies of Part

IV are essentially complete through 1946, and an effort has been made to include all literature through June, 1947.

## 32. GENERAL CRITIQUE OF THE BIOLOGICAL APPLICATION OF ISOTOPES

### A. Introduction

The particular importance of isotopes in biology is related to the fact that, for most of those elements that are constituents of protoplasm, artificial radioactive species can be substituted for normally occurring homologues and used as "tracers" of metabolism and other physiological processes; also that, in the case of a few elements, enriched amounts of the rarer stable species can be introduced into biological systems and also used as tracers. Thus, certain absolute or relative properties of various atomic nuclei permit the biological application of isotopes as tracers.

Of considerable importance also is the study of isotopic behavior and effects per se. This is particularly true of radioactive species in connection with the effects of their ionizing radiations. Again it is physical properties of atomic nuclei that are basic to the phenomena studied.

The biological application of isotopes can be conveniently classified as follows:

- I. Use as labeling agents ("tracers") of normal and abnormal physiology
  - A. As tracers of metabolism
    1. Of intrinsic constituents of the organism
      - a. water
      - b. minerals, including trace elements
      - c. organic substances



2. Of extrinsic substances (abnormal to the organism in form or amount)
  - a. in pharmacological studies
  - b. in toxicological studies
- B. As tracers of non-metabolic processes
  1. Involving cells and other intrinsic complex constituents
  2. Involving foreign substances
    - a. dissolved gases
    - b. colloids and particles of greater than colloidal size
    - c. foreign cells and organisms
- II. Use in the study of the behavior and effects of isotopes per se
  - A. Differential fates of isotopes
  - B. Effects of isotopes
    1. of abnormal concentrations
    2. of radiation (including radiotherapy)

#### B. A survey of useful isotopes

Isotopes that have been used in biological and medical studies belong to 55 elements and are listed in Table 25. In Table 26 are listed: 1, biologically promising isotopes which belong to elements represented in Table 25, but for which no published reports on their biological application have as yet appeared, and 2, potentially useful isotopes of those elements for which no tracer studies have yet been reported. Elements appearing in Table 25 are marked with an asterisk in Table 26. These two tables may be used to make tentative determinations as to whether a useful isotope exists for a projected experiment, and if so, what experimental conditions its successful application may demand.

From Tables 25 and 26 it may be seen that so far slightly less than half (75 out of 163) of the potentially applicable radioactive isotopes listed have been employed in biological experimentation. Unquestionably, many, if not most, of those as yet unemployed will find experimental application in the near future. Most studies with radioactive species have been in the field of tracer work. A number of studies, however, have been on the biological effects of radiation; and a few radioisotopes now have well established applications in clinical medicine.

Eight stable isotopes have been applied to biological problems. Most work with stable isotopes has been with the rarer species of elements existing in more than one stable form. Out of 278 known stable isotopes, 197 are less abundant species of the 60 elements having two or more naturally occurring isotopes; but of the 197, only 7 have known biological applications. Most work with these rarer species has been in tracer studies. However, not all the rarer stable species so far used have been applied in this manner, for certain isotopes have peculiar properties that have made possible, or suggest, their use in radiation studies. For example, both lithium (Li) and boron (B) have rarer isotopes that split when bombarded with accelerated particles. The specific ionization of the radiation released is considerably greater than that attending the accelerated particles themselves. Thus selective localization of Li and B compounds has made possible selective radiation of certain tissues (Bl, Li 1-2). However, these properties are not necessarily restricted to the rarer species of the elements concerned. Beryllium (Be) consisting of a single isotope (Be 9), gives off fast neutrons when bombarded with protons or deuterons; the resulting neutron beams have in turn been used for experimental therapeutic purposes. And finally the more common<sup>of</sup>/the two isotopes of hydrogen (H) - i.e., protium (p, or H 1)



has been suggested for a possible therapeutic role when accelerated to the high energies of the new giant cyclotrons.

From the foregoing discussion it may be seen that radioactive and stable isotopes have applications both in tracer problems and in the study of radiation effects. No exclusive distinction can thus be made between them on either basis. However, for the most part radioactive isotopes are more versatile and, except in a few cases, are the important tracers. By reason of their great variety of radioactive properties, they also offer far more diversified techniques for study of radiation effects.

### C. Isotopes as tracers

1. General considerations. Isotopes in biological tracer work are tools for the elucidation of physiological processes, not objects of study in themselves. Thus, if all the literature on tracer applications were to be exhaustively summarized, an artificial separation of isotopic and non-isotopic studies of the same phenomena would be effected. A rational approach to the literature, therefore, is rather to cite for the isotopes of each element enough representative studies to illustrate their known range of usefulness; to these can be added in many cases speculation as to additional applications. This approach is essentially followed here in the sections on individual elements and groups of elements.

Radioactive species that are adaptable to biological studies exist for most elements. Exceptions to this include : He, Li, B, and Ne, of which the known unstable forms are so short-lived (40 seconds or less in half-life) that it seems unlikely that they will ever find biological application. Certain other elements are greatly limited in this regard by the shortness

of half-life of their longest-lived radioisotopes; these include N, O, Mg, and Al, for the isotopes of which the half-lives are 10.2 minutes or less. F and Si are somewhat unsatisfactory as their best isotopes have half-lives of only about 2 hours and 3 hours respectively. The known isotope of Fr has a half-life of only 21 minutes. But, aside from these 11 elements, all of which are of low atomic weight except francium, the other 85 of the periodic system have radioisotopes of reasonably or very convenient half-lives for biological work.

The use of stable isotopes as tracers for the 60 elements of which more than one species exists is limited by two factors; 1, the expense and technical difficulties involved in concentrating a given species from the isotopic mixture characteristic of an element having more than one stable nuclear form; and 2, the ready availability and convenience of application of at least one radioactive species for most elements. Only in the case of five elements - all of light atomic weight - have practical methods been developed for concentrating the less abundant isotope for tracer studies; namely, for H, C, N, O, and S. For H, C, and S, convenient radioactive species also exist; but successful tracing of N and O must depend in the vast preponderance of cases on the rarer stable forms. For similar reasons, if tracing with Mg is ever to be developed, it would appear likely that some extension in stable isotope tracing must be made. The same considerations may well apply to He, Li, B, Ne, and probably Si. Aluminum is a particularly unfortunate element from this point of view inasmuch as it exists in only one stable form and has no known radioactive species of longer half-life than 6.7 minutes.

The extension of stable isotopic tracing to heavier elements, for which isotopic separation is increasingly difficult and for which convenient



radioactive species are known, would seem to depend upon the desirability of entirely eliminating the effects of the radiation associated with the radioactive species of many of these elements. So far there is little evidence that this will prove a practical necessity; it may well be, however, that even the slight amount of ionization accompanying trace doses will be shown in case of long-lived isotopes to have a deleterious effect, particularly from the genetic aspect, on living organisms.

2. Metabolic tracing. In the realm of metabolic tracing, the role, in normal and pathological states, of elements and compounds normal to the organism is unquestionably the most vital aspect. We deal here with both essential and presumably non-essential elements. In the former category are elements that range from those making up the major organic and inorganic constituents of protoplasm (H, C, N, O, Mg, P, S, and usually K and Ca) to those required by all living substance in minute quantities (Fe and possibly also Mn and Zn - the so-called micronutrient, or trace, elements). The need of certain organisms for additional macronutrient (Na and Cl) and various micronutrient elements "normal" to the protoplasm and protoplasmic products of various organisms embraces the greater part of the periodic system. These, however, usually occur in exceedingly minute amounts. Some of these, nevertheless, may eventually prove to be essential micronutrients.

Actually or potentially useful isotopic labels are known for all elements shown to be essential to living organisms (except possibly aluminum). Universally accepted as essential to all life are the elements H, C, N, O, Mg, P, S, and Fe. Although K and Ca are usually regarded as essential metabolites, there is some evidence that certain bacteria and blue-

green algae may not require one or the other. In addition, certain elements have been shown to be unquestionably essential to certain plants or animals and at least some of these probably are universal micronutrient requirements of living systems on our planet. These elements include: B, Na, Al, Si, Cl, V, Mn, Co, Cu, Zn, Mo, and I. There is also rather good evidence that certain plants require Ga, Cb, and W, and certain animals, Ni and Br. Other elements that have been postulated as essential micronutrients for certain forms are Li, F, Cr, Rb, Sr, Sn, and others. It is quite possible therefore that some 30 or more of the 96 known elements are essential to various forms of living organisms.

So far it has been the metabolism of the macronutrient elements and of two micronutrients, Fe and I (in the higher vertebrates), that has been intensively studied with tracers. Only certain of the micronutrients have been subjected to the tracer approach, including, aside from Fe and I, the elements Mn, Co, Cu, and Zn. Important micronutrients such as B and Mo in plants are still to be investigated, also such probably micronutrients as Ga, Cb, and W in plants and Ni in animals.

The use of isotopic tracers has already divulged a tremendous store of data on the metabolism of essential elements. In many cases, as with much of the intermediary metabolism of organic compounds and the dynamics of electrolytes in body fluids, this information would have otherwise been quite unattainable. In the study of the role of micronutrients, isotopic tracer techniques will very likely supply us with an understanding of mechanisms now poorly or scarcely at all understood, and it may well be that these techniques can, in addition, give us evidence for the essential role of other elements not now definitely known to play an essential role in any living process.



Studies with trace amounts have been carried out for a number of elements not known to be essential to life. Where these elements are normally present in minute amounts in an organism it is possible to elucidate their behavior in the "normal" metabolism of that organism.

The study of the metabolic fate of elements and compounds abnormal to the body in form or amount has also been carried out for a large number of substances. Such investigations have either a toxicological or pharmacological basis, or both.

3. Non-metabolic tracing. Under non-metabolic tracing may be included study of the behavior and fate of normal body constituents above the purely biochemical level, e.g., erythrocytes; and of foreign substances, e.g., bacteria, inert gases, etc.

In some cases, it is impossible to draw a clear distinction between metabolic and non-metabolic tracing because the labeling isotope for the latter type of experiment often also has a metabolic role. For example, the labeling of erythrocytes with radioiron has been used to study the movement and mixing of blood (Fe 6, 19, etc.); however, the iron of labeled hemoglobin has an active role in the metabolic pool and for long term experiments the turnover of hemoglobin iron must be considered in any experiment with labeled erythrocytes. Similarly in studying the movement of labeled bacteria and other foreign cells, the metabolic interchange of the labeling atoms between these cells and their host environment must be considered.

#### 4. Theory and techniques of tracing physiological processes.

The fundamental techniques of isotopic tracing are directed toward the answering of two main questions: 1, what path or paths does a labeled material take in moving and changing within a biological system; and 2, at what rate does such a process or processes occur.

The first of these questions can in some cases be partly or even entirely answered by other than isotopic techniques. For example, at the metabolic level, the tracing of an abnormal substance, or of abnormal amounts of a normal constituent, can be carried out in many cases by microchemical or even macrochemical procedures. Nevertheless, the use of isotopes even in these cases permits of greater accuracy and in many cases much greater simplicity of experimental procedure. For the study of normal metabolism, moreover, non-isotopic techniques offer at best a crude approximation of what isotopic procedures can clearly reveal. Though chemical analysis of parts of a biological system can demonstrate what the constituents are at any given time, they can tell relatively little as to the exact pattern of movement by which those constituents have become incorporated into the system. With tracers, such problems as the permeability of substances and the transport of microconstituents can be readily revealed.

The study of rates of biological processes is even less satisfactory if restricted to non-isotopic techniques. In fact only those rates can be conveniently studied non-isotopically that deal either with the production of end products or with changes in the absolute amounts or relative proportions of given constituents in a biological system. In one vital aspect, the functioning of biological systems can be satisfactorily studied only with isotopes; this is the pattern and the rate of change, or turnover rate, of intermediary substances in dynamic equilibrium in a biological system. Even though we might know by other means all the substances that enter a system and all the substances that leave it, we cannot determine merely by chemical means all the intermediate steps and in particular, the rates at which the transformations involved are occurring. However, with isotopes as labeling agents it is possible to put molecular groupings into a system



such that they behave essentially as do similar groups already present, but are nevertheless distinguishable by virtue of slight mass differences in the case of stable isotopes or of radioactive decay phenomena in the case of radioactive isotopes.

The use of an isotope as a tracer for any given purpose involves: 1, its availability in a suitable form or its preparation as, or incorporation into, the material to be labeled; 2, its administration in a suitable manner to the biological system to be studied; 3, its recovery and measurement, or in some cases its measurement directly in vivo.

With radioisotopes all of these steps must be carried out with precautions against the overexposure of personnel to ionizing radiation. This involved avoidance not only of irradiation at the time of experimentation but also of contamination by, or assimilation of, radioactive materials, and hence continued irradiation. Where human beings are the biological systems studied, care must also be taken against exceeding the safe tracer dose - usually given as 0.1 r.e.p. of total body irradiation per day.

The preparation of isotopically labeled substances involves the conservation of valuable materials. Therefore, special synthetic processes, in which yields are as high as possible, often must be evolved. In some cases it is possible to obtain labeled materials through biosynthetic processes; in such cases an isotope is introduced into a living system, and the desired labeled material isolated later.

The administration of labeled tracer substances presents no unusual features other than those associated with health protection against irradiation in the case of radioisotopes.

The measurement of isotopes involves a number of specialized

techniques. Quite different procedures must be applied to stable as opposed to radioactive species. At the present time stable isotopes may be measured only in the mass spectrometer except for deuterium and heavy oxygen, for which additional techniques are available. The latter depend either on measurements of density or on measurements of refractive index of highly purified mixtures of water and deuterium oxide ("heavy water"). (Cf. sections 22 and 23 on stable isotope measurement.)

The radioactive isotopes may be detected or measured by three principal techniques; *in vitro*, *in vivo*, and autoradiographic. The *in vitro* and *in vivo* methods involve the use of the Geiger-Müller counter, an electroscopic counter, or an ionization chamber; the autoradiographic, the use of a sensitive photographic emulsion.

The *in vitro* techniques of measurement are carried out on samples removed from the biological system under study and are highly varied in procedure. The choice of method depends upon the manner in which a given isotope must be prepared for effective counting. (Cf. sections 18, 19 and 21 on radiation counters, and 24-28 on the preparation of samples for measurement.)

The *in vivo* method is characterized by measurement of a radioisotope in the intact system. This may be accomplished only where the emanations of an isotope are sufficiently penetrating to permit the approximation of a counter to the experimental subject and the detection of particles of nuclear disintegration originating within the latter.

$\gamma$ -emitters and high energy  $\beta$ -emitters can be studied by this method. Most measurements carried out in this way are largely qualitative although, with a precise understanding of the geometry of the counting arrangement, and the distribution of the isotope within the system, accurate quantitative measurements are possible.



The autoradiographic technique is also largely qualitative.

It involves the approximation of a biological sample to a photographic film sensitive to the radiations of the isotope used. (Cf. section 29.) The resulting pattern on the developed film illustrates the distribution and, to a certain degree, the differential concentration of the isotope on the surface of the sample and, to a greater or lesser extent, depending upon the thickness of the sample and the energy of the radiated particles, the distribution and concentration in the parts of the sample beneath its surface. The most satisfactory autoradiographs are those made from very thin samples, e.g., sections of tissues or organs. Techniques have recently been developed for the simultaneous mounting of a tissue section and a sensitive gelatin layer on a microscope slide (I 112, 114). The film may be developed after an appropriate interval, and the section stained; there thus results a stained section superimposed on its radioautograph (or vice versa) from which a precise picture of the isotope distribution can be determined.

5. Analysis by isotopic dilution. A tracer application of isotopes that deserves mention is their use in biochemical analysis, namely, analysis by isotopic dilution. Here we are, strictly speaking, not dealing with a biological but rather with a chemical procedure. However, the convenience of the method is such that it has great significance for biological problems, particularly at the metabolic level.

When a given mixture is to be analysed for the absolute content of a constituent, it may be very difficult to purify out the latter quantitatively. In such cases it may be very simple to introduce a precisely known amount of the constituent to be determined, labeled with a suitable isotopic indicator. Once this is thoroughly mixed into the material to be

analysed, a sample of the constituent may be prepared in pure form, but non-quantitatively. Then by determining the amount of dilution that the labeled substance introduced has undergone, it is possible to calculate the amount originally present in the mixture according to the following formula:

$$x_2 = x_1 \left( \frac{C_1}{C_f} - 1 \right)$$

where  $x_2$  = total amount of the constituent to be determined,  
 $x_1$  = amount of labeled constituent introduced,  
 $C_1$  = initial concentration of labeling isotope, and  
 $C_f$  = final concentration.

In the case of radioisotopes, concentrations (C) are most easily measure in terms of number of counts per unit time per unit weight or volume of the substance labeled, these measurements being made with the Geiger-Müller counter. Where the isotope is of short half-life, appropriate corrections for decay must be made. When very small amounts of labeled material are added to a great excess of material being measured, as is true in much work with radioactive isotopes, the formula may be simplified to the form:

$$x_2 = x_1 \frac{C_1}{C_f}$$

by ignoring the negligible correction for the mass or volume of the added material.

In the case of stable isotopes, concentrations are measured in terms of atoms per cent of the labeling isotope present in excess over its normal abundance. Such measurements may be easily calculated from mass spectrometer data or, in the case of hydrogen and heavy oxygen,



from data derived by the other techniques available for these isotopes. In the case of deuterium vs. protium, of which the atomic weights are significantly different, a correction for the changes in molecular weight accompanying isotopic dilution should be made when low molecular weight substances highly enriched in deuterium are used for measurements by the isotopic dilution method. The formula then becomes

$$x_2 = x_1 \left( \frac{C_1}{C_f} - 1 \right) \frac{M_2}{M_1}$$

wherein  $M_1$  and  $M_2$  are the average molecular weights of the tagged compound added and the resulting tagged mixture respectively.

#### D. The differential behavior and effects of isotopes

So far there have been few demonstrations that the different stable isotopic species of a given element behave differently in living systems. However, in the case of hydrogen, the differential behavior of deuterium vs. protium has been extensively shown. High concentrations of deuterium oxide ("heavy water") have been demonstrated to have toxic effects on organisms from bacteria to mice (D31). Evidence also has been accumulated for the differential use of carbon and oxygen isotopes by living systems (C51, O3).

Most of the radioactive isotopes in use are of sufficiently high molecular weight that no differential effect due to the difference between their masses and those of their normally occurring stable analogues is to be expected. However, tritium will most certainly prove an exception to this inasmuch as the difference between its behavior and that of ordinary hydrogen will be greater than that already shown between deuterium and protium.

The decay pattern of any given isotope is, of course, unaffected by its participation in a biological system. However, its radioactivity can have decided effects when the isotope is present in sufficiently high concentration. In terms of the effect of ionizing radiation, its effect may be profound.

Radioactive isotopes have been used in a number of studies on the effects of ionizing radiation on biological systems. In particular, interest has been focused on those isotopes that can be administered in a form that will be selectively localized in specific parts of such systems. The basis for the use of radioisotopes in therapy lies in the phenomena of differential concentration.



Table 25

Important stable and radioactive isotopes that have been used in biological  
and medical investigations

Element		± Isotope		Some important problems to which isotope has been applied
Z	Name	Stable	Radioactive	
		*H 1		High speed proton irradiation (suggested)
1	*Hydrogen	*H 2 (D)		Intermediary metabolism, body water turnover and content
			H 3 (T)	Body water content, photosynthesis
3	Lithium	Li 6 (in natural element)		Slow neutron therapy of experimen- tal tumors
			Be 7	Absorption, distribution and ex- cretion
4	Beryllium	Be 9 (natural element)		Fast neutron irradiation and thera- py
5	Boron	B 10 (in natural element)		Slow neutron therapy of experi- mental tumors
		*C 13		Intermediary metabolism
6	*Carbon		C 11	CO <sub>2</sub> metabolism in plants and ani- mals; CO distribution and elimin- ation
			C 14	Photosynthesis, other preliminary tracer work

Element		Isotope		Some important problems to which isotope has been applied
Z	Name	Stable	Radioactive	
7	*Nitrogen		N 13	Respiratory gas exchange; supposed nitrogen fixation by barley
		*N 15		Intermediary metabolism
8	*Oxygen	*O 18		Photosynthesis; bacterial fractionation
9	Fluorine		F 18	Bone and tooth physiology and chemistry
11	*Sodium		Na 22	Retention in congestive heart disease; effect of dietary chloride deficiency
			Na 24	Electrolyte metabolism; adrenal physiology; therapy of leukemia
12	*Magnesium		Mg 27	Photosynthesis
15	*Phosphorus		P 32	Mineral metabolism; intermediary metabolism; therapy of chronic leukemias, polycythemia vera, etc. and skin lesions; diagnosis of malignancy; colloids localizing in the reticulo-endothelial system
16	*Sulfur	*S 34		Intermediary metabolism
			S 35	Intermediary metabolism; thiamine metabolism; mineral metabolism



Element	Radioactive	Some important problems to which isotope has	
Z	Name	Isotope	been applied
17	*Chlorine	Cl 38	Mineral metabolism
18	Argon	A 41	Respiratory gas exchange; blood circulatory pattern
19	*Potassium	K 42	Mineral metabolism; adrenal physiology
20	*Calcium	(Ca 41) ‡ Ca 45	Mineral metabolism
25	*Manganese	Mn 52 (Mn 54)	Distribution of colloidal MnO <sub>2</sub> in reticulo-endothelial system
		(Mn 52)	Mineral metabolism
		Mn 54	
		Mn 56	Mineral metabolism
		Fe 55	Mineral metabolism; blood physiology; blood preservation
26	*Iron	(Fe 55)	Mineral metabolism; blood physiology; blood preservation
		Fe 59	
		Fe 59	Mineral metabolism; blood physiology
		Co 56	
27	*Cobalt	(Co 57)	Mineral metabolism
		Co 58	
29	*Copper	Cu 64	Mineral metabolism
30	*Zinc	Zn 65	Mineral metabolism

Element		Radioactive	Some important problems to which isotope has
Z	Name	Isotope	been applied
33	Arsenic	As 74	Absorption, distribution and excretion; experimental filariasis
34	Selenium	Se 83	Absorption, distribution, and excretion
35	*Bromine	Br 82	Electrolyte exchange; thyroid physiology; distribution of brominated dyes
36	Krypton	Kr 79,81	Respiratory gas exchange; blood circulatory pattern
37	Rubidium	Rb 86	Electrolyte exchange
38	Strontium	Sr 85	Absorption, distribution, and excretion
		Sr 89	Bone physiology; therapy of bone sarcoma
		Sr 90	Absorption, distribution, and excretion
39	Yttrium	Y 88	Absorption, distribution, and excretion
		Y 91	Absorption, distribution, and excretion; colloids in reticuloendothelial system
40	Zirconium	Zr 89	Absorption, distribution, and excretion
		Zr 95	Absorption, distribution, and excretion; colloids localizing in reticuloendothelial system
41	Columbium	Cb 95	Absorption, distribution, and excretion; colloids localizing in reticuloendothelial system
44	Ruthenium	Ru 103	Absorption, distribution, and excretion
		Ru 106	
51	Antimony	Sb 124	Absorption, distribution, and excretion; experimental filariasis



Element	Radioactive	Some important problems to which isotope has	
Z	Name	Isotope	been applied
52	Tellurium	Te 121	Absorption, distribution, and excretion
		Te 127	Absorption, distribution, and excretion
		(Te 129)	
53	*Iodine	I 128	Iodine metabolism and thyroid physiology
		I 130	Iodine metabolism and thyroid physiology
		I 130	Therapy of thyrotoxicosis
		(I 131)	
54	Xenon		Iodine metabolism and thyroid physiology; therapy of thyrotoxicosis and metastatic thyroid carcinoma; absorption of insulin
		Xe 127	Respiratory gas exchange; blood circulatory pattern
		Xe 133	Absorption and distribution
55	Cesium	Cs 134	Absorption, distribution, and excretion <sub>h</sub>
		Cs 135	Absorption, distribution, and excretion
56	Barium	Ba 133	Absorption, distribution, and excretion <sub>h</sub>
		Ba 140	Absorption, distribution, and excretion
57	Lanthanum	La 140	Absorption, distribution, and excretion
58	Cerium	Ce 141	Absorption, distribution, and excretion
		Ce 144	Absorption, distribution, and excretion

Element		Radioactive	Some important problems to which isotope has
Z	Name	Isotope	been applied
59	Praseodymium	Pr 143	Absorption, distribution, and excretion
61	Element 61	61 147	Absorption, distribution, and excretion
79	Gold	Au 198	Absorption, distribution, and excretion; chrysotherapy in arthritis
80	Mercury	Hg 197	Mercury vapor as industrial health hazard
82	Lead	Pb 210 (RaD)	Absorption, distribution, and excretion
		Pb 212 (ThB)	Absorption, distribution, and excretion
83	Bismuth	Bi 210 (RaE)	Absorption, distribution, and excretion
85	Astatine	At 211	Thyroid physiology
86	Radon	Rn 220 (Tn)	Elimination in breath
			Numerous studies on uptake and elimination in breath, distribution, etc.; treatment of various malignancies and dermatoses
		Rn 222	
88	Radium	Ra 226	Numerous studies on distribution, toxicity, etc., treatment of various malignancies and dermatoses
		Ra 228 (MsTh <sub>1</sub> )	
		Th 228 (RdTh)	Absorption, distribution, and excretion
90	Thorium (normal element)	Th 232	Numerous studies on distribution, toxicity, etc.
		Th 234 (UX <sub>1</sub> )	Absorption, distribution, and excretion
91	Protoactinium	Pa 231	Absorption, distribution, and excretion



Element	Radioactive	Some important problems to which isotope has	
Z	Name	Isotope	been applied
		Normal element	Numerous studies on distribution, toxicity, etc.
92	Uranium	U 235 (AcU)	Production of slow neutrons; colloids localizing in reticuloendothelial system
93	Neptunium	Np 239	Absorption, distribution, and excretion
94	Plutonium	Pu 239	Absorption, distribution, and excretion
95	Americium	Am 241	Absorption, distribution, and excretion
96	Curium	Cm 242	Absorption, distribution, and excretion

\* Elements (and their naturally occurring isotopes) known or believed to be essential in mammalian nutrition are marked with an asterisk; those for which unanimity is lacking are also marked with a question mark.

± An isotope is placed in parentheses if it occurs together with another isotope or isotopes (of the same element) used for tracer work, but is itself not significant for the tracer purposes to which the mixture may be applied. Two or more isotopes are connected by a brace if they occur together in tracer preparations and are of about equal importance.

6 Personal communication from Dr. J. G. Hamilton.

Table 26

POTENTIALLY VALUABLE TRACER ISOTOPES, ESPECIALLY THOSE OF ELEMENTS FOR  
WHICH BIOLOGICAL STUDIES HAVE NOT YET BEEN CARRIED OUT

Element		Isotope	Half-life (or percent abundance)	Radiation		
Z	Name			Type	Energy in mev	
					Particle	$\gamma$ -ray
2	Helium	He	3 stable (~ 10 <sup>-5</sup> )			
3	*Lithium	Li	6 stable (7.5)			
4	*Beryllium	Be	10 7.3 x 10 <sup>6</sup> y	$\beta^-$ , $\gamma$	0.65	0.5
5	*Boron	B	10 stable (18.4)			
8	*Oxygen	O	15 126 sec.	$\beta^+$	1.7	
			17 stable (0.041)			
10	Neon	Ne	21 stable (0.27)			
			22 stable (9.73)			
12	*Magnesium	Mg	25 stable (11.5)			
			26 stable (11.1)			
13	Aluminum	Al	28 2.4 m	$\beta^-$ , $\gamma$	3.3	1.82
			29 6.7 m	$\beta^-$	2.5	
14	Silicon	Si	29 stable (6.2)			
			30 stable (4.2)			
			31 170 m	$\beta^-$	1.8	



				Radiation		
Element		Isotope	Half-life (or percent abundance)	Type	Energy in mev	
Z	Name				Particle	$\gamma$ -ray
16	*Sulfur	S	33	stable (0.74)		
			36	stable (0.016)		
17	*Chlorine	Cl	36	$10^5$ y	$\beta^+, K, \beta^-$	0.64 ( $\beta^-$ )
			37	stable (24.6)		
18	*Argon	A	37	34.1 d	K	
19	*Potassium	K	40	$1.42 \times 10^9$ y (0.012)	$\beta^-, \gamma, K$	0.4 2
			41	stable (6.61)		
20	*Calcium	Ca	42	stable (9.64)		
			43	stable (0.15)		
			44	stable (2.06)		
			48	stable (0.19)		
21	Scandium	Sc	44	2.44 d	I.T., $e^-, \gamma$	0.28, 1.33
			46	85 d	$\beta^-, \gamma, K$	0.26, 1.5 1.25
			48	44 h	$\beta^-, \gamma$	0.64 1.35
22	Titanium	Ti	51	72 d	$\beta^-, \gamma$	0.36 1.0
23	Vanadium	V	48	16 d	$\beta^+, K, \gamma$	1.0 or 0.58 1.05 or 1.5-
			49	600 d	K	
24	Chromium	Cr	51	26.5 d	$K, \gamma, e^-$	0.5, 1.0

Element		Isotope	Half-life (or percent abundance)	Radiation			
Z	Name			Type	Energy in mev		
					Particle	$\gamma$ -ray	
26	*Iron	Fe	54	stable (6.04)			
			57	stable (2.11)			
			58	stable (0.28)			
27	*Cobalt	Co	60	5.3 y	$\beta^-,\gamma$	0.30	1.1,1.3
28	Nickel	Ni	57	36 h	$\beta^+$	0.67	0.05
			59	150y	K, $e^-$		
29	*Copper	Cu	61	3.4 h	$\beta^+,K$	0.9	
			65	stable (29.87)			
30	*Zinc	Zn	69	13.8 h	I.T., $\gamma$		0.439
			69	57 m	$\beta^-$	1.0	
31	Gallium	Ga	66	9.4 h	$\beta^+$	3.1	
			67	83 h	K, $\gamma,e^-$		0.0925,0.180, 0.297
			72	14.25 h	$\beta^-,\gamma$	0.77,2.4	2.4,8.4
32	Germanium	Ge	69	~195 d	?		
			71	11 d	K, $e^-$ (?)		0.6
			71	40 h	$\beta^+$	1.2	
			77	12 h	$\beta^-$	1.9	
33	*Arsenic	As	72 73	90 h	K, $e^-$		
			76	26.8 h	$\beta^-,\gamma$ ; $\beta^+$ , K, $\gamma$	1.1,1.7,2.7	3.2,2.2,1.5
			77	40 h	$\beta^-$	0.7	



Element		Isotope	Half-life (or percent abundance)	Type	Radiation	
Z	Name				Energy in mev	
					Particle	$\gamma$ -ray
34	*Selenium	Se	75 115 d	K, $\gamma$ ,e <sup>-</sup>		0.50
35	*Bromine	Br	80 4.4 h	I.T.,e <sup>-</sup>		0.049,0.037 or 0.025
36	*Krypton	Kr	85 4.5 h	$\beta^-$	0.85 or 0.94	0.17,0.37
			85 ~10 y	$\beta^-$	0.74	
39	*Yttrium	Y	90 65 h	$\beta^-$	2.2	
40	*Zirconium	Zr	97 17 h	$\beta^-$ , $\gamma$	1.9	0.8
41	*Columbium	Cb	92 11 d	$\beta^-$ , $\gamma$	1.138	1.0
42	Molybdenum	Mo	99 67 h	$\beta^-$ , $\gamma$	1.5	0.4
43	Technetium	Tc	96 4.2 d	K, $\gamma$ ,e <sup>-</sup>		0.96
			97 15 y	K(?)		
			97 93 d	K, $\gamma$ ,e <sup>-</sup>		0.097
			99 2 x 10 <sup>6</sup> y	$\beta^-$	0.38	
44	*Ruthenium	Ru	97 2.8 d	K, $\gamma$ ,e <sup>-</sup>		0.23
45	Rhodium	Rh	102 210 d	$\beta^-$ , $\beta^+$ , $\gamma$	1.1	?
			105 36.5 h	$\beta^+$ , $\gamma$	0.6	0.33
46	Palladium	Pd	103 17.0 d	K		
			112 21 h	$\beta^-$	0.2	
47	Silver	Ag	106 8.2 d	K, $\gamma$ ,e <sup>-</sup>	1.2	1.06,0.69
			110 225 d	K,e <sup>-</sup> , $\gamma$	2.8	
			111 7.5 d	$\beta^-$	0.8,0.24	
48	Cadmium	Cd	109 330 d	K		
			115 40 d	$\beta^-$ , $\gamma$	1.7,1.8	0.5
			115 2.5 d		1.11,0.56,1.20	

Element		Isotope	Half-life (or percent abundance)	Type	Radiation	
Z	Name				Energy in mev	
					Particle	$\gamma$ -ray
49	Indium	In 111	2.7 d	$K, \gamma, e^-$		0.17, 0.25
		114	48 d	I.T., $e^-$		0.19
		115	4.42 h	I.T., $e^-$	$e^-$ : 0.308, 0.332	0.34, 0.78, 1.21, 1.79, 2.29
50	Tin	Sn 113	70-105 d	$K, \gamma, e^-$		0.085
		121	~60 h	$\beta^-$	0.76	
		123	10 d	$\beta^-$	0.26	
51	*Antimony	Sb 122	2.8 d	$\beta^-, \gamma$	0.81, 1.64	0.96
		125	2.7 y	$\beta^-, \gamma$	0.03, 0.7, 0.6	0.6, 0.027
		127	80 h	$\beta^-, \gamma$	1.15	0.72
		129	4.2 h	$\beta^-$	?	
52	*Tellurium	Te 131	30 h	I.T., $e^-$	0.147, 0.175	0.177
53	*Iodine	I 124	4 d	$\beta^+, \gamma$	?	0.1
		?125	56 d	K		
		126	13.0 d	$\beta^-, \gamma$	1.1	0.5
		135	6.6 h	$\beta^-, \gamma$	1.35, 1.5	1.6, 1.3
55	*Cesium	Cs 132	7.1 d	$K, \gamma, e^-$		0.145
		134	1.7 y	$\beta^-, \gamma$	0.9	0.776, 1.35, 0.584
		136	10.5 d	$K, \beta^-, \gamma, e^-$	0.2	?
		137	33 y	$\beta^-, \gamma$	0.5, 0.8	0.75
56	*Lanthanum	La 137	17.5 h	$K, \gamma$		0.88
		141	3.7 h	$\beta^-$	2.8	
58	*Cerium	Ce 140	140 d	I.T., $\gamma$		0.21
		144	275 d	$\beta^-$	0.348	



Element		Isotope	Half-life (or percent abundance)	Radiation		
Z	Name			Type	Energy in mev	
					Particle	$\gamma$ -ray
59	*Praseodymium	Pr 142	19.3 h	$\beta^-,\gamma$	2.14	1.9
60	Neodymium	Nd 147	11.0 d	$\beta^-,\gamma,e$	0.4	0.58
		149	2 h	$\beta^-,\gamma$	1.5	
61	*(Unnamed)	61 148	5.3 d	$\beta^-,\gamma$	2	?
		149	47 h	$\beta^-,\gamma$	1.1	0.25
62	Samarium	Sm 153	46 h	I.T., $\beta^-,\gamma$	0.73, 0.70	0.6, 0.11
63	Europium	Eu 152	9.2 h	$\beta^-,\gamma,e$	1.88	0.123, 0.163 0.725
		154	7 y	$\beta^-,\gamma$	0.9	?
		155	2 y	$\beta^-,\gamma$	0.23	0.0844
		156	15.4 d	$\beta^-,\gamma$	0.5, 2.5	2.0
		157	15.4 h	$\beta^-,\gamma$	1.7, 1.0	0.6, 0.2
64	Gadolinium	Gd 159	8 h	$\beta^-$	?	
65	Terbium	Tb 160	3.9 h	$\beta^-$	?	
		160	72 d	$\beta^-,\gamma$	0.70	?
66	Dysprosium	Dy 165	2.5 h	$\beta^-,\gamma$	1.20	?
67	Holmium	Ho 166	27.5 h	$\beta^-$	1.6	
68	Erbium	Er 169 171	12 h	$\beta^-$	?	
69	Thulium	Tm 170	105 d	$\beta^-$	1.1	
70	Ytterbium	Yb 175	45 d	$\beta^-$	0.3	
		175	4.2 d	$\beta^-,\gamma$	1.15	0.35
71	Lutecium	Lu 176	5.67 h	K, $\beta^-,\gamma$	1.150	?
		177	6.8 d	$\beta^-,\gamma$	0.440	0.2

Element		Isotope	Half-life (or percent abundance)	Radiation			
				Type	Energy in mev		
Z	Name				Particle	$\gamma$ -ray	
72	Hafnium	Hf	181 46 d	$\beta^-$	0.8	0.5	
73	Tantalum	Ta	180 8.2 h	$K, e^-, \gamma$	$e^-$ : <0.5	?	
			182 120 d	$\beta^-, \gamma$	1.0	1.6	
74	Tungsten	W	185 77 d	$\beta^-, \gamma$	0.55-0.65	?	
			187 24.1 h	$\beta^-, \gamma$	1.4	0.87	
75	Rhenium	Re	184 52d	$K, \beta^+, \gamma$	0.22-0.26	0.85	
			186 92.8 h	$\beta^-$	1.07		
			188 18.9 h	$\beta^-, \gamma$	2.5	0.8	
76	Osmium	Os	185 94.7 d	$K, \gamma$		?	
			191 31.9 h	$\beta^-, \gamma$	0.95	1.17	
			193 17 d	$\beta^-, \gamma$	0.35	?	
77	Iridium	Ir	190 10.7 d	$\beta^+, \gamma, e$	0.91	0.25	
			192 75 d	$\beta^-, \gamma$	0.59	0.53	
			194 19 h	$\beta^-, \gamma$	2.2	1.35	
78	Platinum	Pt	197 18 h	$\beta^-$	0.65		
			197 3.3 d	$\beta^-, \gamma$	?	?	
79	*Gold	Au	199 3.3 d	$\beta^-, \gamma$	1.01	0.45	
80	* Mercury	Hg	203 51.5 d	$\beta^-, \gamma$	0.46	0.30	
81	Thallium	Tl	202 11.8 d	$K, \gamma, e^-$		0.40	
			206 3.5 y	$\beta^-$	0.87		
82	*Lead	Pb	203 52 h	I.T.(?) or $K(?) e^-, \gamma$	?	0.45	
			209 3.0 h	$\beta^-$	0.7		



Element		Isotope	Half-life (or percent abundance)	Radiation		
Z	Name			Type	Energy in mev	
					Particle	$\gamma$ -ray
83	*Bismuth	Bi 205	10-15 h	K, $e^-$ , $\gamma$		?
		206	6.4 d	K, $e^-$ , $\gamma$		0.93
		207	6.4 d	K(?) $e^-$ , $\gamma$		0.74
		208	$10^4$ y	K, $e^-$ , $\beta^+$ , $\gamma$	?	?
84	Polonium	Po 206	9 d	K, $\alpha$ , $\gamma$	$\alpha$ : 5.2	?
		207	5.7 h	K		
		208	3 y	$\alpha$	$\alpha$ : 5.14	
		210	140 d	$\alpha$ , $\gamma$	$\alpha$ : 5.298	?
87	Francium	Fa 223	21 m	$\beta^-$ , $\gamma$	1.20	> 3
88	Radium	Ra 224	3.64 d	$\alpha$	$\alpha$ : 5.681	
89	Actinium	Ac 227	13.5 y 21 y	$\alpha$ , $\beta^-$	$\alpha$ : 5.0 $\beta^-$ : 0.220	

\*Elements appearing in Table 25.

### 33. ELEMENTS CONSTITUTING MAJOR ORGANIC METABOLITES

#### A. Introduction

For purposes of this Handbook the major elements constituting metabolites are considered to be the following six: H, C, N, O, P, and S. These are the fundamental elements of the various proteins, which form the framework of all living cells. Useful tracer isotopes exist for all six, and at least one isotope has already been applied for each. It may be noted that all these elements play a role in mineral metabolism, but this is of secondary importance to their organic function.

Since the pioneer work of Schoenheimer who initiated the use of isotopes in the study of intermediary organic metabolism slightly more than a decade ago, a very large literature has grown up. The most important generalizing concept that has come out of this work has been that of the dynamic state, or equilibrium of all organic body constituents (D 331). Work on intermediate metabolism of organic substances - carbohydrates, fats, proteins, etc. - has shown that all are undergoing a continuous process of breakdown and resynthesis, even seemingly inert substances such as stored body fat.

The application of isotopes has already solved many important problems in the metabolism of organic substances, but the future unquestionably holds a far vaster range of application.

#### B. Carbon

Carbon which forms the "backbone" of all organic compounds, has three useful isotopes for tracer work; the rarer stable species, C 13, and two unstable species, C 11 and C 14. In application, C 11 is limited to short-term



experiments by reason of its short half-life (20.5 minutes), whereas C 13 (stable) and C 14 (over 4000 year half-life) are valuable for long-term experiments - particularly those in intermediary metabolism. C 11 is useful for in vivo studies since, as a  $\beta^+$  emitter, it has penetrating annihilation gamma rays. It can be prepared in carrier-free form in the cyclotron by the reaction  $B\ 10\ (d,n)\ C\ 11$ . Because of excellent cyclotron yields, it can also be used for making simple organic compounds for preliminary studies to be followed later with more exacting studies using C 13 or C 14. C 13 must of course be measured with the mass spectrometer. And C 14, which emits weak  $\beta^-$  rays and no gamma rays, must be counted under fairly exacting conditions, i.e., with a thin mica-window G-M counter and exact geometry or, in the case of low activities, in a gas counter or ionization chamber. It has a definite advantage over C 13 in providing a greater sensitivity of measurement. It can be prepared in high specific activity in the nuclear pile reaction by the reaction  $N\ 14\ (n,p)\ C\ 14$ , but in practical operation a considerable amount of stable C contaminates this process.

The most significant work with C 11 has been studies on carbon dioxide utilization by animals and plants (C 123,124) and on carbon monoxide metabolism (C 107). In the latter case it has been shown that CO is not oxidized, at least over a two hour period in the human body, into CO<sub>2</sub>.

With C 13 a rather large series of experiments have been performed dealing with the intermediary metabolism of carbohydrates, fats, and, to a lesser degree, amino-acids (C 15). Much information has been derived on the role of their precursors. Among the most important results has been discarding of the idea that certain simple substances are the specific precursors of more complex compounds - for example, lactic acid as a precursor of glycogen. Rather, they are now regarded as contributors to the general metabolic

pool from which the complex substances are formed. In connection with CO<sub>2</sub> metabolism, a number of studies have established a revolutionary fact, namely, that CO<sub>2</sub> is not merely an end-product of organic metabolism in the higher animals, but actually an essential compound in certain organic metabolic reactions, although admittedly these do not compare in complexity with bacterial chemo- and photosynthesis or plant photosynthesis.

C 14, having only recently become available in appreciable quantities from the nuclear pile reactor, has not yet had widespread application. However it is in all probability destined to become the isotope of choice as a tracer in most future research in intermediary metabolism. In fact, it shows promise of becoming the most important single radioisotope available for tracer work. The most important work so far reported is probably the demonstration with C 14 that radioactively labeled carbonate may be laid down in rat bone for at least several weeks without showing any change in concentration; this suggests great caution in the application of this isotope to humans (C 11).

### C. Hydrogen

Hydrogen, which with carbon is found in all organic compounds and which with oxygen comprises, in the form of water, the greater part of living organisms, has two useful tracer isotopes - the rare stable species, deuterium, H 2 (or D), and the radioactive species, tritium, H 3 (or T). Deuterium was the earliest stable tracer used and has had wide application. Tritium has had very limited use partly because of the technical difficulties inherent in measuring its very weak  $\beta^-$  rays, which can be detected only in a gas counter, and partly because of its limited supply. Accurate gas counters have now been developed; and ample supplies should be forthcoming from the nuclear



pile reactors by the reaction  $\text{Li } 6 \text{ (n,}\alpha\text{) H } 3$ . This isotope should therefore have increasing application, particularly in view of the fact that a considerable increase in sensitivity of measurement is possible with compounds labeled with T over that with compounds labeled with D. Furthermore, its long half-life (about 30 years) makes it available for complex syntheses and long-term experiments.

D has been used to label a wide variety of organic compounds. These are summarized in a recent text by Kamen (Gen 44). Whenever D may be introduced in a relatively stable position in an organic molecule, i.e., attached to a carbon atom where it is generally stably bound, it becomes essentially an auxiliary label for carbon. The first experiments with isotopically labeled compounds were with D-labeled fats (D 330). Previous to this work it had been thought that depot or storage fat was a biological energy store and was outside the general metabolism, becoming active only in times of need. However with the D label the surprising thing was soon shown that these fats were in a state of fairly rapid turnover and, furthermore, that fatty acids or fats of one type could be converted into fats in which the acid moiety was changed by deletions or additions to the carbon chain or by desaturation. It has been shown on the other hand that such dietarily essential fatty acids as linoleic acid are not formed from other fatty acids.

Since the initial work with fats, there has grown up an extensive literature on a number of classes of organic compounds labeled with D at stable positions.

D has also been used, in the form of "heavy water", in the study of body water content (by the isotope dilution method) (D 147,148,190) and body water turnover in fish (D 145,146) and man (D 147,148) and in a number of other problems in the movement of water in the vertebrate body (D 31,71,72,81, etc.)

T has had very limited application. The only work so far reported have been two papers: one on photosynthesis (T 1) and one on the determination of total body water (T 2) in a manner analagous to that in which D has been used.

The use of D and T as tracers, especially as auxiliary tracers of C, has far from been exhausted and particularly important future applications should come with these isotopes used in doubly or multiply labeled compounds.

#### D. Oxygen

Oxygen has two rarer stable isotopes, O 17 and O 18, that offer considerable potentialities for biological application. So far, however, only O 18 has been used in tracer work, and for very limited purposes. The unstable species of longest half-life is O 15 (126 seconds); this has not been employed for tracer work and does not offer much promise.

Although there have been several chemical tracer studies with O 15, the only biological experiment so far reported is a study on photosynthesis (O 7) in which it was shown that the O<sub>2</sub> released in this vital process is derived from water and not from CO<sub>2</sub>. Other biological studies with the oxygen isotopes have been limited to analyses of their relative abundance in the O<sub>2</sub> evolved in photosynthesis (O 56) and in bacterial metabolism (O 3).

There remains for the future, therefore, the vast field of intermediary organic metabolism in which tracer work with O isotopes may be expected to reveal much fundamental information.

#### E. Nitrogen

Nitrogen, which plays an essential role in the peptide linkage of proteins, has two biologically useful isotopes - a short-lived unstable species, N 13 (10.13 minutes half -life) and a rarer stable species, N 15.



N 13 may be made in the cyclotron by the reaction  $C\ 12(d,n)N\ 13$  but it is not a promising agent despite excellent cyclotron yields. It has had very limited biological application as a tracer. The only study so far reported is one supposedly demonstrating the fixation of nitrogen by a non-leguminous plant (N 45). However, subsequent work with N 15 (N 12) has tended to disprove this.

N 15 on the other hand has been extensively used as a tracer, particularly in the study of the intermediary metabolism of amino-acids and proteins (N 48,81, etc.).

An observation of particular interest has been the fact that proteins must be highly labile molecules in which the peptide bonds are undergoing continual rupture and reclosure with freeing and exchange of amino-groups. A further important observation has been that, insofar as the essential amino-acids are concerned, it is the carbon chain rather than the intact molecule that cannot be synthesized. A process of de- and reamination of all acids goes on continuously in biological systems; and it has further been found that, when N 15 labeled ammonia is administered to organisms ranging from viruses to higher plants and animals, it becomes widely distributed in the constituent proteins of the organism. In regard to nitrogenous waste products, N 15 has been particularly useful in giving a clear cut answer to the source of creatine and creatinine (N 48,81). The sources of creatine are glycine, the amidine group of arginine and the methyl group of methionine. In the mammal all creatinine is derived directly from body creatine, and the reaction is irreversible in vivo.

The use of N 15 for labeling amino-acids, especially coupled with C 13 or C 14 in the carbon chains, will unquestionably reveal a vast amount of as yet unknown facts of protein metabolism. It is through such studies that we may

derive some understanding of the complexities of protoplasm and genetic continuity.

#### F. Sulfur

For sulfur a component of many proteins and certain nutrilites essential for many organisms, there have been two isotopes applied to biological problems -- a rare stable species, S 34, and an unstable species, S 35 ( 87.1 day half-life). There are two other rare stable species that may conceivably find tracer application, S 33 and S 36.

S 34 has had very limited application, so far having been applied only to the study of the conversion of labeled methionine to cystine in vivo (S 31).

S 35 has been available in relatively limited quantities until recently. The nuclear pile reaction Cl 35 (n,p) S 35 is superior in yield to the several cyclotron reactions. Nevertheless, S 35 has been applied to a number of studies on S metabolism, particularly the intermediary metabolism of S-containing amino-acids and proteins (S 20-25) and the excretion of S wastes as sulfate (S 7,22). It has been used to demonstrate that inorganic sulfate is not reduced and incorporated into the body protein (S 22) and that inorganic sulfide is largely oxidized to sulfate although small amounts may be incorporated into protein (S 6-7,19). Preliminary studies have also been carried out with labeled thiamin, which is in a state of dynamic equilibrium just as the major organic metabolites (S 2).

#### G. Phosphorus

Phosphorus, a constituent of bone, of many organic energy storing and transferring systems, and of nucleoprotein, which is basic to all life as we know it, has but one stable isotope, P 31, and for tracer work but one bio-



logically useful form, the radioactive species P 32 (14.3 day half-life). There are more publications dealing with this isotope than with any other species, stable or radioactive. P 32 may be produced in excellent yields from the cyclotron by the reaction P 31 (d,p) P 32 and in the uranium pile, by the reactions P 31 (n, $\gamma$ ) P 32 and S 32 (n,p) P 32.

The mineral metabolism of P has been investigated by a number of workers. It was early found that P rapidly appears in the bone and that there was a slow, but definite turnover of bone phosphates (P 69,70). The excretion of P was shown to take place through both urine and feces (P 190), although less than 10% escaped by the latter route. Other studies have demonstrated the rates at which the inorganic plasma phosphate becomes incorporated into the organic metabolic pool (P 58,186, etc.) and the permeability of erythrocytes (P 91,159,181,etc.) and other cellular membranes to the phosphate ion (P 143, 184, etc.).

The major tracer studies with P 32 in intermediary metabolism have been on the formation and fate of two important classes of organic compounds: the phospholipids (P 58, etc.) and the nucleoproteins (P 2,6, etc.). It has been demonstrated that the main site of phospholipid production for systemic use is the liver, although the kidney and intestinal mucosa synthesize their own phospholipid independently of the liver (P 122). Considerable work has been done on the turnover of ribose- and desoxyribosenucleoprotein in various tissues. When labeled inorganic phosphate is administered to the mammal, it is distributed in the nucleic acid moiety of the nucleoprotein of all tissues (P 340,341). Furthermore this distribution correlates with the known metabolic and growth characteristics of the various tissues. Desoxyribosenucleic acid, being a nuclear constituent, turns over at a much greater rate in such rapidly growing tissues as the spleen, growing liver, and neoplasms, than in the adult liver, the cells of which, while metabolically very active, are not undergoing

many mitoses (P 3,197). Ribosenucleic acid on the other hand, being largely a cytoplasmic constituent, turns over in the liver as much as 33 times as fast as desoxyribosenucleic acid (P 373); it also has a high turnover rate in the spleen and intestinal mucosa. Such facts correlate well with the known importance of these organs in protein metabolism and with the hypothesis that the ribosenucleotides play a role in the synthesis of proteins.

P 32 has also found an important role in the treatment of certain blood dyscrasias (Cf. section 37).

Despite the wide and intensive application of this isotope, its potentialities in the study of vital processes have been by no means exhausted.



## 34. ELEMENTS CONSTITUTING MAJOR MINERAL METABOLITES

### A. Introduction

For purposes of this handbook the major elements constituting mineral metabolites have been selected on the basis of their role in the metabolism of higher animals and accordingly are the following five: Na, Mg, Cl, K, and Ca. H, C, O, and P are also of major importance in mineral metabolism, but have already been considered in the preceding section. The five listed are the elements that form, along with H, C (as carbonates), O (in all complex ions), and P (as phosphates), the main essential electrolytes of the protoplasm and extracellular and vascular fluids of higher animals. In addition, Mg and Ca, along with C, O, and P, are the main mineral constituents of bone - the main skeletal material of the higher vertebrates. Useful tracer isotopes have been applied for all, although tracing with Mg has been limited to one study.

The study of mineral metabolism with isotopic tracers began in 1935 with the work of Chievitz and Hevesy on phosphorus uptake and distribution in the rat (P 69). Since that time a rather considerable body of literature has grown up particularly in connection with the dynamics of electrolytes in the mammal and with the metabolism of bone.

### B. Sodium

Sodium, like phosphorus, has but one stable isotope and consequently its tracers are radioactive. Two useful species exist - Na 24, the short lived form (14.8 hour half life) produced in the cyclotron by the reaction  $\text{Na}^{23}(\text{d}, \text{p})\text{Na}^{24}$  and in the nuclear pile by the reaction  $\text{Na}^{23}(\text{n}, \text{p})\text{Na}^{24}$ ,

and Na<sup>22</sup>, the long-lived form (3 year half life), produced in the cyclotron by the reaction  $\text{Mg}^{24}(\text{d}, \alpha)\text{Na}^{22}$ . Both Na 24 and Na 22 can be used for in vivo studies as penetrating nuclear gamma rays attend the decay of both. Since Na forms the most important extracellular cation in vertebrates, study of its electrolyte dynamics is of great significance.

Studies with Na 24 have been directed toward the determination of the time and mode of normal uptake (Na 9, 12, 15, 32, 37, 38, etc.), distribution (Na 18, 34, 51, etc.), and excretion (Na 32, 40, 62, 68, etc.) of Na in the mammal. The time of equilibration of Na injected in man has been found with Na 24 to be between 9 and 12 hours (Na 51). Initially the spread is rapid - for two or three hours - to a volume of fluid representing about one-fourth of the body weight. It has been suggested that this represents the extracellular fluid volume.

Na 24 has had wide application to studies of vascular and cellular permeability. It has been possible to demonstrate that the turnover between the blood Na and that of the intestinal lumen is very large (Na 81, 82), being equal in the dog to the total plasma Na in about 83 minutes. In connection with the passage of Na across the placental barrier in several species, including man, it has been found that the transfer unit weight of placenta increases greatly as gestation proceeds (Na 19-25, 28-31, etc.). The penetration of Na<sup>+</sup> into erythrocytes has been investigated by a number of workers (Na 8, 56, 84), and a considerable species difference shown to exist in the rate of this process. In general, however, Na can be demonstrated to diffuse in and out of the red cell.

The role of the mammalian adrenal in Na metabolism has also been investigated with Na 24 (Na 1-5); and Na 24 has been used in the experimental therapy of human and mouse leukemia (cf. Section 37).



With Na 22 much longer term experiments are of course possible than with Na 24. So far this isotope has had relatively limited application. It has been used to demonstrate the increase in the Na space of the rat body under conditions of dietary chloride deficiency (Na 10) and to show the great depression of Na excretion in congestive heart failure in man - as much as 1/50 of the normal clearance (Na 72).

### C. Potassium

Potassium at the present time has but one useful species for biological tracer work - K 42 (of 12.4 hour half life), produced in the cyclotron largely by the reaction  $K41(d,p)K42$  and in the nuclear pile by the reaction  $K41(n,\gamma)K42$ .  $K^+$  is an almost universally essential intracellular cation; in the mammal it serves as the main cation within the cells in contrast with Na in the extracellular fluids. In ascending the periodic system K is the first element that has a naturally occurring, rare, long-lived radioactive isotope; this species - K 40 (about  $10^9$  year half life) - has been speculated upon as conferring on K some of its physiological properties (K 19, 35, 38, 41, 49), but there has been no adequate confirmation of any of these views (K 19). Some evidence exists, however, that biological systems may deal with the isotopes of potassium in a slightly different manner (K 17, 57).

The half life of K 42 limits it to short-term experiments. Nevertheless, a number of studies of K uptake (K 13, 25) and distribution (K 16, 18, 22, 29, 50) have been carried out. In mammals injected with labeled  $K^+$ , the ion penetrates rapidly into most tissues of the body, the testes, brain, and erythrocytes being slowest to exchange intracellular with plasma K (K 18, 50). In tissues with rapid penetration - liver, heart, kidney, etc. - the total K has a relative activity higher than the simultaneous plasma value for the first 1-2 hours after administration, particularly

after intraperitoneal injection.

The penetration of  $K^+$  into erythrocytes has been investigated by several workers (K 11, 12, 14, 39, 44, 45, 47, and 56). As with  $Na^+$  a considerable species difference in permeability and exchangeability has been shown.

The physiology of the adrenal cortex has also been studied with K 42 (K 1-5).

Long-term tracer studies of K metabolism may become possible if the rarer naturally occurring species - K 41 (stable) and K 42 (radioactive) - can be concentrated in a practical manner or if an artificial species of long half life is discovered.

#### D. Calcium

Calcium, the most abundant positive mineral element of the mammalian body, is largely found in bone, but the small amount occurring in the plasma and inside cells is of great physiological significance - in neuromuscular irritability, blood coagulation, cellular permeability, and certain enzymatic systems. In tracer work the one radioactive species so far used - Ca 45 (180 day half life) - has had rather limited application because of poor cyclotron yields from the reaction  $Ca44(d,p)Ca45$ . It is now, however, available in much larger quantities from the nuclear pile by the reaction  $Ca44(n,\gamma)Ca45$  and should have greatly increased utilization. The cyclotron reaction producing Ca 45 also results in some Ca 41 (8.5 day half life) - by  $Ca40(d,p)Ca41$ . However, this latter species decays by K capture and emits only feeble x-rays, which are difficult of detection. Ca 45 can presumably be prepared in carrier free state in the nuclear pile reaction by the reaction  $(Sc45(n,p)Ca45)$ .



Studies with Ca 45 have so far been limited to a few investigations, primarily on the uptake of Ca by calcified tissues. Ca 45 is stored almost entirely in bone (Ca 3, 8, 9) with traces appearing throughout the soft tissue. Vitamin D promotes the absorption of Ca from the digestive tract and the mineralization of the bones of rachitic rats (Ca 5).

Much work on bone metabolism has been done by substituting radioactive Sr for Ca by reason of the similar metabolic behavior of these two elements. For citations to this work see section 36, part B.

#### E. Magnesium

Despite the important biological role of magnesium - as an essential element for all known forms of life - it has scarcely been studied by tracer isotopes. The radioactive species of longest half life - Mg 24, producible in the cyclotron by the reaction  $Mg^{26}(d,p)Mg^{27}$ , has a half life of only 10.2 minutes. It has been used in but one biological experiment (Mg 1), in which its incorporation into chlorophyll by an alga and by barley was shown. By the time chlorophylls a and b could be separated, however, the activity of the Mg 27 was too weak for satisfactory measurement, and therefore no interconversion of the two types of photosynthetic pigments could be demonstrated using the Mg label.

When the rarer stable species, Mg 25 and Mg 26, are prepared in enriched form, it should be possible to investigate not only the role of Mg in photosynthesis, but also its other known vital functions - in enzyme systems, bone metabolism, cellular permeability, etc.

#### F. Chlorine

Chlorine, an essential anion in the higher animals and a micronu-

trient requirement for some plants, has three potentially useful radioactive species - the short-lived forms Cl 24 (33 min. half life) and Cl 38 (27 min. half life) and the long-lived form, Cl 36 ( $10^6$  year half life). So far only Cl 38 has been used in biological experiments; it is made in the cyclotron by the reactions  $\text{Cl}37(d,p)\text{Cl}38$ ;  $\text{Cl}37(n,\gamma)\text{Cl}38$ ; and  $\text{K}41(n,\alpha)\text{Cl}38$ . Cl 34 can be produced in the cyclotron by two reactions -  $\text{P}31(\alpha,n)\text{Cl}34$  and  $\text{S}33(d,n)\text{Cl}34$ . Cl 36, which can be produced in significant amounts only in the nuclear pile- by the reaction  $\text{Cl}35(n,\gamma)\text{Cl}36$  - has only recently become available for tracer work.

The short half life of Cl 38 has limited tracer experiments thus far reported for Cl, to short-term studies. When introduced as labeled  $\text{LiCl}$ , Cl 38 rapidly finds its way into the chloride space of such organs and tissues as the kidney, liver, muscles, cartilage, and tendons, but not into that of the testes and pyloric mucosa (Cl 11).  $\text{Cl}^-$  has also been found to penetrate rapidly into erythrocytes (Cl 15). It appears in normal gastric juice very quickly - within 1 to 2 minutes after intravenous injection into the man or dog (Cl 2), but more slowly in the case of achlorhydria (Cl 3).

When Cl 38 is widely available, tracer work with Cl can be much expanded.



A. Introduction

The elements so far considered have major metabolic roles in some or all living systems. In addition to these macronutrient constituents of protoplasm, there are a number of elements that have been recognized as being essential in "trace" amounts in the metabolism of certain organisms at least. Certain of these micronutrient elements - at least Fe and probably also Mn and Zn - are universally required for living systems. A number of others are known to be essential for certain forms of life but not for others.

The elements accepted as essential trace nutrients for purposes of this Handbook are, in order of increasing atomic weight: B, Al, Si, V, Mn, Fe, Co, Cu, Zn, Mo, I. They are arranged somewhat arbitrarily in the following subsections according to their importance in mammalian nutrition; the last five elements (B, Al, Si, Mo, and V) are known to be essential either to plants or to certain of the lower animals, but not to mammals.

B. Iron

Iron, which is regarded as a universally essential trace element in the oxidative enzyme systems of cells, exists in two radioactive forms that have found tracer application - Fe 55 (about 4 year half life) and Fe 59 (47 day half life). A mixture of these isotopes can be produced in the cyclotron by the deuteron bombardment of iron -  $\text{Fe}^{54}(\text{d},\text{p})\text{Fe}^{55}$  and  $\text{Fe}^{58}(\text{d},\text{p})\text{Fe}^{59}$ ; in addition Fe 55 can be made by the reactions  $\text{Mn}^{55}(\text{p},\text{n})\text{Fe}^{55}$  or  $\text{Mn}^{55}(\text{d},2\text{n})\text{Fe}^{55}$ , and Fe 59 by the reaction  $\text{Co}^{59}(\text{n},\text{p})\text{Fe}^{59}$ . In the nuclear pile reaction a mixture of both isotopes can be produced by the bombardment of iron -

$\text{Fe}^{54}(\text{n}, \gamma)\text{Fe}^{55}$  and  $\text{Fe}^{58}(\text{n}, \gamma)\text{Fe}^{59}$ . Counters sensitive to Fe 55 and Fe 59 individually are known and make possible the use of these two isotopes in multiple labeling experiments.

Fe 59 has been the more widely used isotope. It has largely been employed in the study of Fe metabolism and in the determination of the red cell survival time and the total red cell volume in the mammal, especially man. A number of important new facts about Fe metabolism have been demonstrated with Fe 59. Particularly striking has been clearcut proof of the ability of the mammal to conserve Fe supplies by limiting uptake and excretion (Fe 21, 27, 35, 37, 40, 45, etc.). The uptake of Fe is controlled by the presence of a protein which is capable of combining stoichimetrically with 23% of its weight of iron (Fe 37, 40, etc.); this is ferritin (or, in its iron-free state, apoferritin). Ferrous iron is better absorbed than ferric by man (Fe 41, 42, 51). The loss of Fe from the body is largely through wear and tear rather than any of the usual routes of excretion (Fe 2, etc.).

The most important practical result of studies on the survival of red cells has been demonstration of the best method of in vitro storage of blood to be used for transfusions (Fe 14, 64-69); this involves refrigeration, the addition of dextrose to the citrate anticoagulant, the maintenance of a slightly acid reaction of the diluted plasma or resuspension fluid, and optimal dilution. In certain acid-citrate solutions whole blood can be preserved with up to 70% viability for three weeks, whereas cells preserved by the simple addition of citrate are almost entirely broken down within 24 hours in the new host after only two weeks of preservation in vitro (Fe 59).

The Fe 59 - labeled red cell has been used to follow the distribu-



tion of blood (Fe 17, 18, etc.) and to determine the total red cell volume by the intravenous administration of tagged cells of known activity and the recovery of blood samples after allowing time for mixing to approach completion (Fe 16, 17, 19, 24, 29, etc.).

Fe 55 has had relatively little application, but because of its availability in high specific activity from the cyclotron - by the reaction  $^{54}\text{Fe}(d,2n)^{55}\text{Fe}$  - it has been useful for studies on the distribution of tracer amounts. Work with this isotope has shown the rapid turnover of Fe in the bone marrow, its storage in major part in the liver, and its rapid turnover in the small intestine (Fe 8), as well as its minimal excretion in the urine, bile, and feces (Fe 8, 21). An ingenious study with Fe 55 has shown that the parasite of benign tertian malaria (Plasmodium vivax) selectively invades young erythrocytes (Fe 13).

Fe 55 and Fe 59 have been used in double-labeling experiments on red cell survival (Fe 64, 65, etc.). Conceivably the rarer stable species of iron - Fe 54, Fe 57, and Fe 58 - may find use in multiple labeling experiments when they are prepared in enriched form.

### C. Iodine

Iodine, an essential element in vertebrate metabolism, has a number of useful and potentially useful radioactive isotopes. Three species have found biological application - I 128 (24.99 min. half life) produced in the cyclotron by the reactions  $^{127}\text{I}(d,p)^{128}\text{I}$  and  $^{127}\text{I}(n,\gamma)^{128}\text{I}$ ; I 130 (12.6 hour half life) and I 131 (8.0 day half life), produced together in the cyclotron by the reactions  $^{130}\text{Te}(d,2n)^{130}\text{I}$  and  $^{130}\text{Te}(d,n)^{131}\text{I}$  respectively. I 130 and I 131 also occur as fission products, the latter in much greater

quantities; I 130 can be prepared by itself in the cyclotron by the reaction  $\text{Te}130(p,n)\text{I}130$ , and I 131 can be recovered in carrier-free form from the nuclear pile and subsequent decay reaction:  $\text{Te}130(n,\gamma)\text{Te}131 \longrightarrow \text{I}131 + e^-$ . In addition there are several other as yet unapplied species of varying half lives - I 124 (4 days), I 125 (56 day), I 126 (13.0 day), I 133 (22 hour) and I 135 (6.6 hour). Some of these may find biological application.

Early work with iodine was done with I 128 (in some cases produced by bombarding I 127 with neutrons from a radium-beryllium mixture). The concentration of trace amounts of I in the thyroid gland was demonstrated strikingly by this early work (I 38, 61, 62, etc.).

Most recent tracer work has been done with the two isotopes I 130 and I 131, which are produced as a mixture in the cyclotron by the deuteron bombardment of Te. Currently I 131 is used almost exclusively. The primary application of the I label has, of course, been in the study of thyroid physiology.

Before radioactive iodine became available, the entry of I into the thyroid gland could not be studied under physiological conditions. It has become possible with the radioactive species to study not only entry but also the incorporation of I into the thyroid hormone. When minute doses of I are administered to the mammal a high proportion becomes incorporated in the gland - about 60% in the rat by 24 hours (I 83) and about 50% in man (I 7, 37, 59). However, when these small doses are given after pretreatment with pharmacological amounts, the uptake of the labeled material is much reduced (I 39, 61). Initially the inorganic iodide fraction of the thyroid I has a higher specific activity than the organically bound. This becomes incorporated into diiodotyrosine and thyroxine.



Diiodotyrosine turnover in man is thought to take about 24 hours (I 59). For several days the specific activity of the thyroxine I is less than that of the inorganic or diiodotyrosine I, but, while the diiodotyrosine fraction remains more or less constant, the thyroxine activity gradually rises. This is satisfactorily explained by assuming the conversion of diiodotyrosine into thyroxine rather than the direct iodination of thyronine, the non-iodine containing analogue of thyroxine (I 71).

With radioactive iodine it has been possible to study precisely the effects of various extrinsic factors on I metabolism in the thyroid, e.g., pituitary (I 80, 81, etc.), thiourea (I 3), sulfonamides (1 11, 112), goitrogenic substances (I 13), etc.

Radioactive iodine has also provided a therapeutic tool in the treatment of hyperthyroidism (see Section 37).

The use of the iodine label is the best illustration of the invaluable role that radioactive isotopes can play in the study of trace element metabolism.

#### D. Manganese

Manganese, which is known to activate a number of enzymes, but of which the biological role is not yet clearly defined, is nevertheless thought to be a probably micronutrient requirement for all living systems. It has been well established as essential to the growth and reproduction of higher animals. At least three useful radioactive species exist - Mn 52 (6.5 day half life) made in the cyclotron by the reaction  $\text{Cr}52(d, 2n)\text{Mn}52$ , which also produces small amounts of Mn 54 by the reaction  $\text{Cr}54(d, 2n)\text{Mn}54$ ; Mn 54 (310 day half life), made in the cyclotron by the re-

action  $\text{Fe}^{56}(\text{d}, \alpha)\text{Mn}^{54}$ , which is accompanied by the reaction  $\text{Fe}^{54}(\text{d}, \alpha)\text{Mn}^{52}$ ; and Mn 56, available from the cyclotron by the reaction  $\text{Mn}^{55}(\text{d}, \text{p})\text{Mn}^{56}$ .

Tracer experiments have been reported with all three of the isotopes mentioned. Mn 52 (admixed with small amounts of Mn 54) applied to the study of the distribution of colloidal  $\text{MnO}_2$  injected intravenously for therapeutic purposes in man (Mn 6, 9) (cf. Sect. 36). Mn 54 (admixed with small amounts of Mn 52) has had wider use, having been employed to show that tracer amounts of Mn are rapidly excreted in the rat almost entirely in the feces (Mn 4, 5) in the latter Mn 54 is erroneously referred to as Mn56 ) and that, even in the case of perosis in the chicken produced by Mn deficiency, Mn is not deposited to a greater than normal extent in the bone, although it accumulates in the liver in greater amounts than in normal animals (Mn 7). Mn 56 has also been used for the study of Mn distribution in the mammal (Mn 1).

The use of the tracers of Mn have been very limited, and much further work may be anticipated.

#### E. Copper

Copper, known to be an essential micronutrient requirement at least of higher animals and functioning in a number of protein and enzyme complexes, has two potentially useful radioactive species for biological experimentation - Cu 61 (of 3.4 hour half life), and Cu 64 (12.8 hour half life) made as a mixture by the cyclotron reactions  $\text{Ni}^{60}(\text{d}, \text{n})\text{Cu}^{61}$ ,  $\text{Ni}^{61}(\text{d}, 2\text{n})\text{Cu}^{61}$ , and  $\text{Ni}^{64}(\text{d}, 2\text{n})\text{Cu}^{64}$ . In addition Cu 64 can be made in the uran-



ium pile by the reaction  $\text{Cu}^{63}(\text{n}, \gamma)\text{Cu}^{64}$ . Of the two stable species, the rarer one,  $\text{Cu}^{65}$ , may also find tracer application, particularly in view of the relatively short half life of  $\text{Cu}^{64}$ .

So far the few biological studies published have been done with  $\text{Cu}^{64}$ , any associated  $\text{Cu}^{61}$  having decayed away or having been ignored. Studies on the uptake and elimination of tracer amounts of  $\text{Cu}$  fed to rats show that, of that absorbed most goes to the liver in absolute amount, but that it concentrates relatively more in the kidneys than in other organs. Although little is eliminated in the urine ( $\text{Cu}^{3}$ ). following ingestion it appears rapidly in the plasma ( $\text{Cu}^{6}$ ); the uptake is relatively greater in animals having hematopoietic activity increased over normal ( $\text{Cu}^{3}$ ,  $6$ ). Copper in the plasma is largely present bound in some way to protein ( $\text{Cu}^{5}$ ).

#### F. Zinc

Zinc, like manganese, is important in enzymatic functions and may well be a universal micronutrient requirement of living systems. Its essential role in the higher animals has not been unequivocally shown although evidence that it is necessary is all but conclusive. It occurs in several stable and radioactive species of which only one has had biological application -  $\text{Zn}^{65}$  (250 day half life), produced in the cyclotron by the reaction  $\text{Zn}^{64}(\text{n}, \text{p})\text{Zn}^{65}$  and  $\text{Cu}^{65}(\text{d}, 2\text{n})\text{Zn}^{65}$  and in the uranium pile by the reaction  $\text{Zn}^{64}(\text{n}, \gamma)\text{Zn}^{65}$ . Other radioisotopes exist, but of short half life -  $\text{Zn}^{63}$  (38 min.),  $\text{Zn}^{69}$  (13.8 hours),  $\text{Zn}^{69}$  (57 min. - isomer of preceding), and  $\text{Zn}^{72}$  (49 minutes). These offer possible alternatives if it is desired to avoid the very long half

life of Zn 65.

So far the biological experiments with Zn 65 have been limited to a few studies on the fate of Zn administered by various routes (An 1-4). Like Mn, but unlike Co, Zn is excreted by way of the gastrointestinal tract, and relatively little in the urine. It accumulates in the liver from which it is rapidly lost in the bile; it also concentrates to varying degrees in the pancreas, kidney, and spleen.

Further fundamental advances in the understanding of Zn metabolism quite evidently depend upon further application of Zn tracers.

#### G. Cobalt

Cobalt is very likely an essential trace element in the nutrition of higher animals, although unequivocal evidence is lacking. There are a number of radioactive isotopes of which four are formed by the deuteron bombardment of iron - Co 55 (18.0 hours) by  $\text{Fe}^{54}(\text{d},\text{n})\text{Co}^{55}$ ; Co 56 (80 days) by  $\text{Fe}^{56}(\text{d},2\text{n})\text{Co}^{56}$ ; Co 57 (270 days) by  $\text{Fe}^{56}(\text{d},\text{n})\text{Co}^{57}$ ; and Co 58 (72 days) by  $\text{Fe}^{57}(\text{d},\text{n})\text{Co}^{58}$ . From the nuclear pile reaction Co 60 (5.3 year half life) is available by the reaction  $\text{Co}^{59}(\text{n},\gamma)\text{Co}^{60}$ .

The few studies reported have been carried out with mixtures of Co 56, Co 57, and Co 58, of which the first and last make up the more important component; Co 55 decays away in a few days, and consequently targets are allowed to age so that this species can be disregarded. The chief route of excretion of Co is the urine, in contrast to Mn and Zn (Co 1, 2, 4). Ingested Co is only partly absorbed, and the bile is an important, but not the sole pathway for the passage of cobalt from the body into the intestinal tract (Co 3, 4).



## H. Boron

Boron, which is known to be an essential micronutrient of higher plants and some microorganisms, has not been studied by tracer methods. The only possible tracer isotope known is the stable species B 10, which constitutes 18.4% of the element. This species is now available in nearly pure form.

Work has, however, been done with B in the study of the effect of the selective ionization produced by bombarding this element concentrated in tissues (B 1-3) with slow neutrons. These studies have shown that the splitting of B 10 under such conditions may have a therapeutic application.

## I. Aluminum

Aluminum, which is known to be essential to certain plants and protozoans, has also not been studied by tracer techniques. The only available species would seem to be Al 28 and Al 29 with half lives of only 2.4 and 6.7 minutes respectively. At best these offer very limited potentialities.

## J. Silicon

Silicon, which is also known to be essential in the nutrition of certain plants and protozoa and which may also be necessary micronutrient in higher animals, is another element not yet studied by biological tracing methods. Possibly useful species are the two rarer stable species - Si 29 and Si 30 - and the radioactive species, Si 31 (170 min. half life).

#### K. Molybdenum

For molybdenum, an element required by certain higher plants, there is one known radioactive species of convenient half life - Mo 99 (67 hour half life), which suffers, however, by being the parent of radioactive Tc 99. In addition there are a number of stable species that might prove of value.

#### L. Vanadium

Vanadium is an essential part of a metallo-porphyrin respiratory pigment in certain lower chordates. Its metabolism could readily be studied with the radioactive isotope V 48 (16 day half life) and possibly with V 49 (600 day half life).



A. Introduction

Some 22 of the 96 known elements have been considered so far. The remaining 74 are not known to be essential to living systems. However, as already noted in Part 32, there are certain elements for which a vital role has been suggested on evidence of varying strength. For purposes of this Handbook these elements (some 11) are considered in subsection B.

The remaining elements are grouped more or less arbitrarily into 1, elements of common pharmacological and toxicological importance; 2, the noble gases; 3, elements of the lanthanide rare earth series and others in fission; 4, the actinide rare earth series; and 5, other elements.

For the main nuclear reactions producing the isotopes considered in the following subsections, Table 11 should be consulted.

B. Possible Micronutrient Elements

1. General considerations. Eleven elements are treated here as having been regarded as possible trace requirements for animals or plants. This does not complete the list of elements for which such a role has been suggested, but it does cover the principal ones. These elements are Li, F, Cr, Ni, Ga, Br, Rb, Sr, Cb, Sn, and W.

2. Lithium. No tracer work has been reported for Li, which has been found widely present in trace amounts in animals. It has no known radioactive isotope of half life greater than 0.88 seconds, and thus the rarer stable species, Li 6, will presumably have to serve for purposes where changes in systems in dynamic Li equilibrium are to be studied. Some studies have been made with

natural Li on the effect of bombarding Li in tissues with slow neutrons (Li 1-2); like B 10, the bombarded Li 6 nucleus splits with the release of high specific ionization. These studies have given results similar to those obtained with B.

3. Fluorine. The effect of F in making teeth more resistant to caries has led to its being postulated as an essential micronutrient in vertebrates. A few studies have been carried out with F 18 (112 minute half life) on the uptake of F in bone and teeth (F 1-3). These have shown the uptake of F in bone and teeth both in vivo and in vitro. The secretion of F in the submaxillary gland saliva of the cat has also been shown (F 1).

4. Chromium. No tracer work has been carried out for Cr, which has been suggested as a possible trace requirement in certain plants and animals. The radioactive species Cr 51 (26.5 day half life) is available for such studies.

5. Nickel. Ni has been found concentrated in the mammalian pancreas and in the bodies of several invertebrates and may be involved in enzyme systems. Its metabolism has not yet been subjected to tracer studies, although the radioactive isotopes Ni 57 (36 hour half life) and Ni 59 (15 year half life) are available and should prove useful.

6. Gallium. There is strong evidence for the essential role of Ga in certain plants. It has not yet been studied with tracer methods, however. Several potentially useful radioactive species exist - the most promising of these for tracer studies being Ga 67 (83 hour half life).

7. Bromine. Br is present in small amounts as an electrolyte in the vertebrate body - primarily extracellularly like Cl. Although an essential role has been postulated, definitive evidence is lacking.

Tracer studies with the radioactive species Br 82 (34 hour half life)



have been fairly extensive. The bromide ion has been found to behave in general distribution very much like  $\text{Na}^+$  (Br 4). It is completely distributed in the dog body within a period of one to two hours.

Br 82 has also been used to label diazo dyes in studying the escape of colloids from the blood stream (Br 1) and the concentration and detection of dyes in abscesses (Br 8, 9, 10, 15). Certain dyes become bound to plasma proteins, and, when labeled with Br 82, have been used to show in dogs the great increase in capillary permeability to colloids after burns (Br 1).

The significant selective uptake of bromine by the thyroid has also been shown with Br 82 (Br 11).

8. Rubidium. It has been claimed that Rb may actually replace K in the nutrition of certain bacteria. The element is present in trace amounts as an ion in the vertebrate body fluids. Evidence for an essential role is, however, lacking in either case.

There have been a few studies on the behavior of ionic rubidium in biological systems with the use of the radioactive isotope Rb 86 (19.5 day half life). In the dog it closely resembles K in distribution after intravenous injection (Rb 1). The uptake of the element and its concentration from very dilute solutions of  $\text{Rb}^{++}$  by roots of plants has also been demonstrated (Rb 3).

9. Strontium. Sr has been of considerable interest because of the similarity of its fate in vertebrate metabolism to that of Ca. Because of the poor cyclotron yields of Ca 45 considerable study on bone physiology has been carried out using the radioactive isotope Sr 85 (65 day half life) in place of a Ca isotope. Despite its well-known metabolic behavior in the vertebrate, the essential nature of Sr as a trace element has not been established.

Studies with Sr 85 have shown that when injected, the element rapidly concentrates in the skeleton. In the mouse the radioactivity per wet weight of skeleton is about 100 times that of the soft tissues in 24 hours. Of the soft tissues the liver and especially fat show the lowest activity at this time (Sr 12-14).

Studies on bone fracture healing in normal rats and in rats on abnormal vitamin balance have shown that recalcification is less active in vitamin A and D deficient and D-hypervitaminotic rats. In normal rats the callus undergoes most active calcification from 8 to 16 days with normal strength of the broken bone being recovered within 12 to 16 days (Sr 1). In another experiment it was found that hypophysectomized rats treated with growth hormones deposited in a short period essentially the same amount of Sr 85 in the femur and mandible as did untreated hypophysectomized rats. This suggests that mineral deposition in bone is independent of growth hormonal control (Dr 10).

For the therapeutic application of Sr 85 to bone malignancy see Section 37.

10. Columbium. There is suggestive evidence that Cb is an essential trace requirement in certain plants. Tracer work has, however, been very limited and so far carried out with Cb 95 (37 day half life). It has been used in radioactive colloids that localize in the reticuloendothelial system (Cb 1 - see Section 37) and in one experiment with the tracer-free element (Cb 2) in which it was shown that in the rat parenterally administered Cb accumulated about 40% in the bone and was lost therefrom with a half time of about 100 days. (For further discussion of the uptake in bone of fission elements see subsection E).

11. Tin. Although Sn has been found as a trace element rather widely



in animals, no essential physiological role has been demonstrated. Tracer work is yet to be done. There are at least three potentially useful tracer isotopes - the radioactive species Sn 113 (70-105 day half life), Sn 121 (60 hour half life) and Sn 123 (10 day half life).

12. Tungsten. W has been thought to be essential as a micronutrient of certain plants, but not trace work has yet been attempted with it. There are available two potentially useful radioactive species - W 185 (77 day half life) and W 187 (24.1 hour half life).

### C. Elements of Importance in Pharmacology and Toxicology

1. General considerations. The common elements of toxicological and pharmacological importance not already considered are As, Ag, Sb, Au, Hg, Pb, Bi, and Ra. Tracer studies have been carried out for all of these except Ag.

2. Arsenic. As is an important agent in syphilotherapy and the treatment of leukemia. It is also used in trypanocidal and anthelmintic drugs.

Studies with radioactive arsenic have been limited to the isotope As 74 (16 day half life). Tracer experiments have demonstrated the uptake of subcutaneously administered arsenites in the body proteins of the various mammals but have not supported the view that As may replace P in proteins (As 5, 8). In concentration per unit weight of tissue arsenic administered as arsenite is found in largest amounts in the kidney and in decreasing amounts in the liver, epidermis, spleen, lung, and muscle (As 7). In experimental filariasis (Litomosoides carinii infection in the cotton rat) the concentration in the adult worm is only less than in the kidney and liver (As 7).

3. Silver. Potentially valuable radioactive species for tracer work with Ag are particularly the isotopes Ag 106 (8.2 day half life), Ag 110 (225 day half life), and Ag 111 (7.5 day half life).

4. Antimony. Antimony, important in anthelmintic and antiprotozoal agents, has had some tracer application in the form of Sb 124 (60 day half life). When administered to dogs in the form of tartar emetic, it is found to concentrate most highly in the liver and in decreasing amounts in the thyroid, kidney, cortex, pancreas, intestine, spleen, etc. In dogs with filariasis (the heart worm, Dirofilaria immitis) Sb 124 concentrated more highly in the adult worm than in any other tissues except the liver and thyroid (Sb 1,2).

5. Gold. A single tracer study has been reported for Au in the treatment of rheumatoid arthritis. This showed high uptake of the element in the kidney and liver (Au 1).

6. Mercury. Hg, an important industrial poison and therapeutic agent, has had but one tracer study with the radioactive species Hg 197 (23 and 64 hour half lives). It was used to establish the concentration of Hg vapor in a particular industrial observation suspected of causing chronic mercurialism (Hg 1).

7. Lead. Pb is an important industrial poison. It was the first element to be studied biologically by the "tracer" technique - namely, that of substituting for a normally stable element one of its radioactive species (Pb 5) and thus tracing its fate in a biological system (in this case a plant).

Two lead isotopes, both belonging to naturally radioactive series, have been used in the study of the uptake and fate of Pb in organisms - Pb 210 or RaD (22 year half life) and Pb 212 or ThB (10.6 hour half life). Pb 210 belongs to the U series; Pb 212, to the Th series.

Studies with Pb 210 have included the uptake of Pb in erythrocytes (Pb 8), the absorption of Pb tetraethyl (Pb 7), the effect of pectin on the



retention of dietary Pb (Pb 4), etc. Studies with Pb 212 have been on the uptake of Pb by erythrocytes (Pb 1) and the general distribution of Pb in normal and tumor bearing mice (Pb 5).

8. Bismuth. The use of Bi as an antisyphilitic and antiprotozoal agent renders tracer studies of considerable importance. So far only two studies (Bi 1,2) have appeared, both done with Bi 210 or RaE (5 day half life) of the U series. Bi was found upon parenteral injection to be eliminated in the urine and feces, about twice as much in the former as in the latter, and to concentrate most highly in the kidney and somewhat less in the liver.

9. Radium. Ra has presented a toxicological problem particularly in the watch-making industry in connection with the painting of luminous dials. No attempt has been made here to cover the extensive literature on the toxicology and radiation effects of this element. Ra 226 is the common isotope (1596 year half life).

#### D. Noble Gases

The use of radioactive isotopes of three of the heavier gases - Ar, Kr, and Xe - has made possible important studies on respiratory gas exchange and the pattern of blood mixing in the mammal (Ar 1, Kr 1, 2, 4, Xe 1). The marked solubility of Xe in fat has been shown with the radioactive isotopes Xe 127 (34 day half life), (Xe 3) and Xe 133 (7 day half life) (Xe 1).

Isotopes of Rn - Rn 220 or Th (54.5 second half life), and Rn 222 (3.825 day half life) - have been measured or used in studies on the fate of descendants of the Th and U series respectively.

#### E. Rare Earth Elements (Lanthanide Series) and Other Elements

##### in Fission

The fission of U and Pu results in the production of isotopes of elements ranging from number 30 (Zn) to number 63 (B). Fission products therefore include species of almost half the rare earth elements (nos. 57-71) or lanthanide series. Thus elements for which very little biological interest existed before the large scale utilization of the fission process now have assumed considerable importance by virtue of the dangers of contamination by, and irradiation from, their radioactive species as produced in atomic energy installations. A number of the elements occurring in large yields in fission have already been considered, e.g. Sr, Cb, Xe, I, etc. Other elements occurring as fission products for which biological studies have been carried out include (i.e., those not already considered previously) the rare earths La, Ce, Pr, and 61 and the elements Se, Y, Zr, Ru, Te, Cs, and Ba. Studies with all of these except Se, Y, Zr, and Te have been limited to one or two investigations concerned with fission product problems.

No biological studies have as yet been carried out with radioactive species of the rare earth elements not occurring in fission, nor of several fission elements of lighter weight (Ga, Ge, Rh, Pd, etc.).

Extensive work has been carried out by Hamilton and co-workers (Ba 1, Ce 1, 2, etc.) on the distribution of fission product elements in rats, particularly in the liver and bone. Most of these are not taken up in significant amounts from the digestive tract after oral administration, exceptions being Sr, Te, I, Ba, and Cs. Following parenteral injection, however, many are accumulated in the skeleton and eliminated very slowly - Sr, Y, Zr, Cb, Ba, La, Ce, Pr, and 61, but not Ru, Te, I, or Cs. Initially La, Ce, Pr, and 61 accumulate in the liver, but are quite rapidly excreted from this organ. Of the fission elements concentrating in bone those not taken into the body in



appreciable amounts from the digestive tract are retained for long periods of time in the pulmonary tissue when administered intratracheally or by aerosols. Most of what is absorbed deposits in the bone. This has considerable significance in the public health aspects of atomic energy installation especially as chronic radiation of bone by radioactive isotopes localized there has long been known for Ra and recently demonstrated for Sr and Pu (Sr 19, Pu 3) to cause osteosarcomata.

Studies on Se 75 metabolism have been restricted to two papers on the distribution of labeled selenate injected into the rat (Se 1-2). It was found that selenate labeled with Se 83 (30 min. half life) is rapidly converted in the body into volatile organic compounds and eliminated in the breath. Studies on Te with the isotope Te 121 (125 day half life) (Te 1) and a mixture of the isotopes Te 127 (90 day half life) and Te 129 (32 day half life) (Te 2) have shown on the other hand that at first the urine is the principal route of elimination and later is almost equal to the feces; Te is concentrated most highly in the blood, liver, kidneys, apparently whether administered in the tellurous or telluric state.

Radioisotopes of Y, Zr and Cb have been used in colloidal form in the study of blood mixing time and volume (Y 2, Zr 2). Those of Y have found also preliminary therapeutic application in the treatment of leukemias (see Section 37).

#### F. New Rare Earth Elements

##### (Actinide Series)

The new rare earth elements or actinide series begin with Ac (element 89) and include the heaviest known elements. So far eight have been discovered: Ac, Th, Pa, U, Np, Pu, Am, and Cm. Biological studies have been

carried out for all except Ac. No attempt has been made here to cover the extensive literature on the toxicology of Th and U, nor on the application of Th (as Thorotrast) in radiography. Studies with the other five actinides have been recent and as yet rather limited. However, a great deal of work may be expected on Pu, an element of which the isotope Pu 239 is made artificially in large quantities in the uranium pile reaction, but which exists in nature only in minute traces.

Hamilton's comprehensive study of the metabolism of fission elements was done simultaneously with study of the six actinides Th, Pa, Np, Pu, Am, and Cm (Pa 1, etc.). He has found that like La, Ce, Pr, and 61 they concentrate to a high degree in bone when administered parenterally, but are not absorbed in significant amounts from the digestive tract. Radioautographic study has demonstrated that the bone deposition does not occur uniformly in the osseous tissue (as with Sr), but rather in the periosteum, endosteum, and in the region of the trabecular bone. Recent work has also shown that Pu 239 ( 22,000 year half life) in bone can produce malignant change (Pu 3).

#### G. Other Elements

Elements not already covered in the present subsection include two light elements, Sc and Ti, for which no tracer work has been done, and a number of the heavier elements above the lanthanide series - namely, Hf, Ta, Re, Os, Ir, Pt, Tl, Po, At, and Fa. Of the latter only At has been studied biologically.

At has been studied with the isotope At 211 (75 hour half life). In the one published paper dealing with this species (At 2) it has been found to resemble its analogue I quite closely in being concentrated to a high degree in the thyroid.



## 37. ISOTOPES IN THERAPY AND DIAGNOSIS

### A. Introduction

Radium and radon, and their decay products, have been used for over 45 years in the treatment of various malignancies and dermatoses. These applications are familiar to the medical profession as a whole and need not be detailed here. They are reviewed in such books as that of Ellinger (Radiation Therapy, 1941) and others dealing with roentgen and radium therapy.

Isotopes that have been used in therapy and diagnosis are given in Table 27. As indicated therein artificial isotopes of two elements, P and I, have so far been employed in therapy with definite success. Others - of Na, Mn, Sr, Y, Zr, and Cb - have received preliminary trial, but therapeutic techniques with these elements are still in the experimental stage.

A number of isotopes have also been employed for diagnostic purposes. These are discussed in the following subsections.

The isotopes that so far have shown definite value in therapy and diagnosis have been those that demonstrate a fair degree of selective localization, either as the result of their normal fate in metabolism or of their fate as special compounds or colloids. Thus phosphorus concentrates to a small degree in rapidly growing tissue (particularly in the nucleoprotein) and in bone; iodine localizes in the thyroid gland (at least several hundred times the concentration in the rest of the body); and certain colloidal preparations can be made that localize in various parts of the reticuloendothelium.

So far, all techniques of radiation with isotopes, except in the

case of the treatment of hyperthyroidism with radioiodine, have suffered from the limited selectivity of uptake by the diseased tissue over normal tissues. For example, in the treatment of diseases of the bone marrow and lymphatic system with radioactive phosphorus it is impossible to avoid to a greater or lesser extent the irradiation in various parts of the body of those normal cells that metabolize rapidly and others in the immediate vicinity of the latter. Actually in the treatment of polycythemia vera it would be desirable if irradiation could be delivered only to the nucleated red cells and in lymphosarcoma and leukemia only to the offending leukocytes or lymphosarcoma cells, and not to the normal cells, especially the platelet and red cell producing centers. Some progress may be anticipated in the management of these blood dyscrasias by the application of labeled colloids. Recent work (P 2,7) shows that radiation may be limited largely to the liver and spleen by the use of anhydrous colloidal chromic phosphate labeled with P 32, which localized selectively in the reticuloendothelial cells of the liver and spleen when introduced intravascularly in a highly dispersed form. Similar properties have been discovered (Zr 2) for a number of other colloids - of yttrium (Y), zirconium (Zr) and columbium (Cb) - which may be labeled with radioisotopes of these respective elements. Some of the colloids can be concentrated to a high degree in the bone marrow, others in the liver and spleen.

However, for neoplastic diseases in general, localizing substances of adequate selectivity that can be labeled and used for radiotherapy have not been found.

#### B. Radiophosphorus

The first radioisotope to be used in therapy was P 32. Although applied as early as 1936 it was not until 1939 that the first clinical reports (P 239)



of its application to the treatment of chronic leukemia were published. A number of studies followed, which for the period through 1945 have been quite thoroughly reviewed in a recent paper by Reinhard et al. (P297). In the past two years several important papers have appeared on P 32 therapy. Aside from the paper by Reinhard et al., in which the results of treating a large series of patients suffering from leukemias, lymphoblastomata, and other malignant conditions were reported, there have been papers attesting the usefulness of P 32 in the treatment of polycythemia (P 106, 107) comparing the use of radio-phosphorus and the alkylamines (nitrogen mustards) in the treatment of neoplastic and allied diseases of the hematopoietic system (P 210), describing the external application of P 32 to warts, basal cell carcinomata, etc. (P 375), and reporting on the results of 11 years' experience with a large series of patients with leukemia and polycythemia (P 374).

The most important use of P 32 has been in soluble form (in labeled isotonic  $\text{Na}_2\text{HPO}_4$ ) given by mouth or vein in the treatment of blood dyscrasias. The determination and calculation of dosage, routes of administration, and supportive treatment of patients receiving this type of therapy are discussed in most of the works cited.

The general findings of workers using soluble P 32 therapy have been as follows:

- 1) It is at the present time the treatment of choice for many cases of polycythemia (rubra) vera (P 106, 107, 297, 374) (i.e., primary polycythemia, erythremia, or Osler-Vaquez's disease). In most patients complete hematological remission and almost complete symptomatic relief can be effected. A single course of treatment may bring about a remission lasting from six months to several years.
- 2) For the treatment of chronic leukemia, both lymphatic and myelo-

genous, it is at least as satisfactory in producing hematological and symptomatic remissions as x-ray (P 297, 374) and may prolong life somewhat longer (P 374). It is thus of palliative, and not curative value. There is one definite advantage of P 32 over x-ray, namely in that the former practically never produces radiation sickness; in the few cases reported this has been very mild.

- 3) P 32 therapy has little effect on the course of patients with acute or subacute lymphatic, myelogenous, and monocytic leukemia (P 297). It is possibly of the same limited value as x-radiation.
- 4) Lymphoblastomata and related malignancies do not respond more favorably to P 32 than to x-ray.

Complications of soluble P 32 therapy are leukopenia, thrombocytopenia, and anemia, and these constitute limiting factors in the dosage. X-radiation has value in conjunction with P 32 therapy in reducing more rapidly the size of lymph nodes in lymphatic leukemia and in combating splenomegaly, particularly in myeloid leukemia. It has been common experience among workers concerned that therapy with P 32 requires a considerable degree of individualization. The limitations of P 32 in the form of the soluble phosphate for blood diseases have been brought out recently (P 142).

Recently a technique for the use of P 32 in the treatment of skin lesions has been described by Low-Beer (P 248, 375). He soaks a small piece of blotting paper in a labeled phosphate solution and applies this to the surface of the tumor or other skin lesion. The beta-rays from P 32 have a "half-penetration" of about 1 mm. in tissue, i.e.,  $1/2$  of the particles are absorbed in the first millimeter of tissue,  $\frac{1}{2}$  of the remaining in the second millimeter, and so on. This suggests P 32 may prove superior to x-ray or radium in the



treatment of certain radiosensitive superficial skin lesions by avoiding irradiation of the deeper, uninvolved tissues.

P 32 has also been used for experimental therapeutic purposes, in an insoluble colloid, chromic phosphate. Exploratory work during the past few years on the therapy of the splenomegaly and hepatomegaly (unpublished data) of chronic leukemia with this material has actually been carried on. This application differs in no essential manner from similar uses of other radioisotopes. Another possible application of labeled chromic phosphate and colloids with similar properties is their use in the interstitial infiltration of chemically inert radioactive material into malignant growths, as suggested by work (P 11) on the injection of chromic phosphate into the tissue around transplanted mouse tumors. This shows that chromic phosphate remains at the point of injection and that the radioactive material can cause regression of mammary tumors under a certain size. It is possible that a similar procedure may prove of some value in the treatment of human malignancies especially in inoperable sites.

The use of P 32 as a possible diagnostic tool has been suggested by Low-Beer and associates (P 249, 250). They have found in a few cases that, if small doses of labeled  $\text{Na}_2\text{HPO}_4$  are given to women with suspected breast carcinoma, the activity of the superficially located, malignant lesion (except for slowly growing mucoid carcinomata) is 25% or more above that of the surrounding tissue of the skin. Benign lesions in their series consistently showed less than 25% greater activity.

The use of P 32 has thus been shown to have considerable therapeutic and possible diagnostic value. Further research may well expend its clinical usefulness in the form of other inorganic or organic compounds.

### C. Radioiodine

The therapeutic use of radioactive iodine was reported upon for the first time simultaneously in 1942 (I 25, 36) for the treatment of hyperthyroidism (i.e., thyrotoxicosis, Grave's disease, Basedow's disease, etc.). Comprehensive reports on two series of patients with hyperthyroidism have appeared recently (I 7, 37).

For therapeutic purposes carrier-free radioiodine in the form of an aqueous NaI solution is used, being administered by mouth. In the two most recent reports (I 7, 37), the iodine has consisted of a mixture of I 130 and I 131, of which the former has been the clinically more important component. The determination and calculation of dosage are given in both papers.

In one series (I 37) about 80% of the patients having thyroids of 60 to 75 grams in size and treated with an appropriate dose of radioiodine have been effectively cured. A complication of this form of therapy has been myxedema, resulting from an excessive depression of thyroid function, but as yet there have been no other post-irradiation effects such as the induction of carcinoma. The ultimate evaluation of this form of therapy, as compared with other methods, must await more extensive work and the passage of time.

In the last few years workers have also reported a few cases in which treatment of iodine-metabolizing thyroid malignancy has met with partial or considerable success when radioiodine has been used (I 65, 66, 73, 105, 106). One patient with a metastatic thyroid adenocarcinoma metastases took up iodine and responded favorably to radioiodine therapy administered on three occasions - in March, 1943, April, 1944, and March, 1945. It would, therefore, appear that such treatment can be of value of those thyroid malignancies in which iodine is concentrated.

As a diagnostic tool for the determination of the level of the thyroid function, radioiodine appears to offer good clinical possibilities. So far



most of the publications dealing with thyroid physiology as studied with radioiodine have been in the nature of fundamental investigations rather than of diagnostic developments. However, it has been shown that radioiodine can be used in distinguishing between simple hyperthyroidism and the ophthalmopathic type (I 34, 35).

In general the use of iodine for the treatment and diagnosis of certain thyroid diseases appears highly promising.

#### D. Other Isotopes in Therapy and Diagnosis

The use of isotopes of sodium, manganese, and strontium in therapy has been reported by various workers in the last few years. In addition, recent work with phosphate, yttrium, zirconium, and columbium colloids shows considerable promise.

Radiosodium (Na 24) as labeled NaCl has been applied to the treatment of chronic leukemia (Na 58, 80). One group of workers observed favorable results in 7 cases of chronic lymphatic leukemia (Na 80), but the report extended only over a period of 150 days. Another worker (Na 58), who treated five cases of leukemia with radiosodium and radiophosphorus, found that P 32 gave a much better response. A more recent paper (Na 17) on the effect of Na 24 on normal and leukemic mice gives further suggestion that this form of therapy may prove comparable to total body roentgen radiation. It was found that the hematological response in normal animals was roughly the same with Na 24 as with equivalent roentgen irradiation. However, roentgen irradiation was not compared with Na 24 therapy in leukemic animals, which appeared to show, after administration of the radiosodium, a more rapid, although less prolonged fall in the leukocyte count than did the normal. There is as yet insufficient published data for an evaluation of radiosodium therapy in chronic leukemia, but it is expected that the results

would be similar to those following total body irradiation with x-rays, since there is no selective localization of sodium.

The usefulness of radiosodium as a diagnostic tool is evident from a recent review (Na 86) in which it is reported that in a number of circulatory diseases (arteriosclerosis, Raynaud's disease, etc.) and injuries (trench- and immersion-foot, frost-bite, etc.) of the extremities Na 24 has proved of considerable value in determining the status of the circulation. Since it can be measured by applying a G-M counter to the surface of the skin and thus detecting its penetrating gamma rays, its distribution in the blood, and extracellular tissue fluids can be followed. With this technique of measuring tissue vascularity it has been possible to determine in a number of cases whether surgery is indicated and if so, at what point the amputation should be performed. Similar possibilities exist with the use of radioactive inert gases.

The use of radiostrontium (Sr 89) for the therapy of bone malignancies has been suggested on several occasions because of the concentration of this element in bone analogously with calcium (Sr 8, 9, 12). The most detailed discussion is that of Lawrence (Sr 8), who gave preliminary results for the treatment of primary (osteogenic) and metastatic (breast and prostate) carcinoma in a number of cases. A comprehensive report on this material is still to be published. Actually, however, it is unlikely that diffuse irradiation of bone and marrow for relatively localized malignant growths will prove of much value, particularly in view of the danger of marrow depression. Nevertheless beneficial results have been obtained in the treatment of metastatic prostate cancer in the way of slowing down of the malignant process and control of pain.



A number of radioactive colloids have been used in preliminary therapeutic studies. These include, as already mentioned, anhydrous chromic phosphate (P 217), which localizes almost entirely in the liver and spleen, and colloids of several elements, radioisotopes of which occur as fission products (Y, Zr, Cb); the latter colloids may, depending upon the method of preparation, concentrate almost exclusively in the liver and spleen or go in equal concentration into the bone marrow (Zr 2). Because of the relative abundance of Y, Zr, and Cb in fission, there is a potentially rich source of their radioactive species for such investigations and for possible widespread clinical application. Investigations with radiomanganese as labeled colloidal manganese dioxide in an aqueous medium with gelatin as a protective colloid have recently been reported upon (Mn 6, 9). These suggest the possibility that  $MnO_2$  may be localized upon intravenous injection in the lymphoid reticuloendothelium. In addition to the intravascular use of these colloids there are also, as mentioned, possible applications in interstitial infiltration of malignant growths (P 11). In general the use of labeled colloidal materials is promising and deserves thorough clinical trial.

Although P and I radioisotopes are the only artificial species for which therapeutic applications have been developed, it seems quite likely that in a few years a number of different isotopes will have well accepted clinical uses. In addition to the elements already mentioned, there are important possibilities in the labeling of organic compounds with long-lived radiocarbon - C 14 - and radiohydrogen or tritium - H 3 or T. If radiation is ever to prove a vital tool for the palliation or cure of malignancy, the only possible way for accomplishing this end would

seem, from our present perspective, to be the discovery of organic substances that undergo highly selective localization in various types of cancer cells in contrast to those of normal tissue and that can be labeled with a suitable radioisotope. Tritium with the low penetrating power of its beta rays and its rapid turnover in the body is particularly interesting in this regard. If it can be put in relatively stable positions in localizing compounds, it will expend most of its ionizing power within the concentrating cells. Potentially it is an ideal radiotherapeutic agent.

A discussion of radiotherapy with isotopes would not be complete without mention of the possible role of fissionable isotopes - i.e., of uranium - U 235 - and plutonium - Pu 239 - and of other isotopes that release large amounts of ionizing radiation upon being bombarded with slow neutrons - i.e., of lithium - Li 6 - and boron - B 10. If these materials can be localized in given tissues and organs and the region bombarded with slow neutrons, a significantly high radiation can be conferred on the isotope containing tissue than on the normal or uninvolved tissue through which the neutrons also must pass. It has been shown (B 1) that pieces of transplantable mouse tumor soaked in boric acid solution and then irradiated in vitro with slow neutrons before inoculation into new hosts showed a significantly lower percentage of "takes" than control tumor pieces soaked in boric acid, but not irradiated. Also if lithium or boron salts are infiltrated into mouse tumors in vivo and the host animals bombarded with slow neutrons (B 2, 3), there is a significant increase in tumor regression over that in bombarded but uninjected controls.

Finally there should be mentioned the possible therapeutic use of charged nuclear particles - protons, deuterons, and alpha particles -



to high energies in the cyclotron and other heavy particle accelerators. This would be an isotopic application of sorts inasmuch as the nuclei of single species of hydrogen and helium are being employed. None of these has been used clinically as yet.

Table 27. ISOTOPES USED IN RADIOTHERAPY AND CLINICAL DIAGNOSIS

Isotope	Half-life	Radiation			Form in which used	Use
		Type	Energy in mev			
			Particle	$\gamma$ -ray		
Na 24	14.8 h	$\beta^-,\gamma$	1.4	1.4, 2.8	Na*Cl	Treatment of chronic leukemia; determination of circulatory insufficiency.
P 32	14.3 d	$\beta^-$	1.69		Na <sub>2</sub> HP*O <sub>4</sub> (by mouth or vein)	Chronic leukemias; polycythemia vera; diagnosis of breast carcinoma
					(in blotting paper applied to skin)	Treatment of basal cell carcinoma
Mn 52	6.5 d	$\beta^-,\gamma,K$	0.77	1.0	Mn*O <sub>2</sub> colloid (by vein)	Treatment of lymphoblastomata
Sr 89	55 d	$\beta^-$	1.50		Sr* lactate (by vein)	Treatment of osteosarcoma and metastatic malignancy of bone
Y 91	57 d	$\beta^-$	1.6		Y* colloids (by vein)	Therapy of leukemia ‡
I 130	12.6 h	$\beta^-,\gamma$	0.61, 1.03	0.417, 0.537, 0.667, 0.744	NaI $\ddagger$ (by mouth)	Treatment of thyrotoxicosis
I 131	8.0 d	$\beta^-,\gamma$	0.687	0.4		
Rn 222	3.825 d	$\alpha$	5.486		Radon ointment; radon "seeds" etc.	Treatment of variety of neoplasms, dermatoses, etc.
Ra 226	1590 y	$\alpha,\gamma$	4.791	0.19	Radium bromide in capsules, etc.	
* Some of atoms radioactive						† Personal communication from Dr. J. W. Goiman
						‡ Carrier free

\* Some of atoms radioactive

† Personal communication from Dr. J. W. Goiman

‡ Carrier free



## 38. BIOLOGICAL EFFECTS OF THE NATURAL RADIOACTIVE ELEMENTS

### A. Introduction

The naturally radioactive elements with the exception of  $K^{40}$  may be divided into three groups. These groups, the so-called radioactive series, are named from the heaviest element in each; the uranium, the actinouranium, and the thorium series. Each consists of the parent element and its decay products, 12 or 13 to 16 elements, the last of which is a non-radioactive lead isotope of mass 206, 207, and 208 respectively for the three series (see Fig. 82).

Only a few of these isotopes have been investigated with respect to biological action. In the uranium series, radium (Ra), radon (Rn), radiolead (RaD), polonium (RaF or Po); and in the thorium series, thorium (Th) are the principal elements which have been used in biological investigation. In the second series, actino-uranium,  $U^{235}$ , has recently been used as a source of fission recoils in a study of the biological effects of fission.

The biological effects of these elements and their radiations have been studied on four classes of material; isolated compounds or systems, simple organisms, plants, and animals. In addition, radium and radon have been used extensively in therapy. The literature on these therapeutic uses is so vast, that it will not be reviewed here.

### B. Organic Substances

In the case of compounds of biological importance, most of the experimentation has been done with the  $\alpha$ ,  $\beta$ , and  $\gamma$  radiations. Breger and Burton (2) tested the action of particles from radon on fatty acids and naphthalenic acid. Acetic, caproic, lauric, and palmitic acids, in the presence of 100 mc Rn, produced  $H_2$ ,  $CO_2$ ,  $CH_4$  and some of the higher hydrocarbons. The product of

a similar exposure of naphthalenic acid was a naphthalene derivative. From their data it may be concluded that the action of  $\alpha$  particles on compounds of this type is by decarboxylation and dehydrogenation, and is not sufficient to split the benzene ring. Proteins also are changed by radiations from radium. Fricke (3) demonstrated flocculation of pepsin, trypsin, oxyhemoglobin, complement and egg albumin; and Khenokh (4) showed irreversible coagulation of gelatin sols following a decrease in viscosity and pH after treatment with  $\alpha$ ,  $\beta$ , and  $\gamma$  rays from Ra. The destruction was greater in an 0.5% than in a 1.0% sol and was accompanied by release of ammonia nitrogen. Thiamin exposed to glass radon seeds was partially destroyed (5), although irradiation of mice to the lethal dose gave no change in thiamin concentration of blood or liver. The in vitro damage was not accompanied by splitting of the thiamin molecule since the thiazole or pyrimidine intermediates were not destroyed. To these reports of the action of radiations from the naturally radioactive elements on biological compounds, should be added the observation of Vernoni (6) that treatment of benzpyrenes with  $\gamma$  rays increased the rate at which tumors grew when the irradiated substance was applied to rats.

### C. Micro-Organisms

The naturally radioactive compounds have also been studied in relation to "simple" organisms; phage, virus, bacteria, slime, molds, and algae. The diameters of bacteriophage  $\phi$ -x-174 (7), and vaccinia (8,9), tobacco mosaic (10), and lymphogranuloma (11) virus have been calculated from inactivation by  $\alpha$ , and  $\gamma$  rays of Ra, Rn, and Po on the assumption that a single ionization destroys phage or virus. The values so obtained are within the range of data collected by other means for the same organisms. Bonet-Maury and Bulgakov (7) calculated for phage  $\phi$ -x-174, a diameter of  $18 \pm 5$  m $\mu$ . The diameter for the same phage calculated from centrifugation data was 16 m $\mu$ , and from x-ray data, 17 m $\mu$ .  
The



inactivation of bacteria, slime molds, and algae by radiations from Ra, Rn, and Po has also been reported. For bacteria the inactivation dose of  $\gamma$  (Ra),  $x$ -, and  $\alpha$  (Po) radiation increases in that order and for any given radiation, the inactivation dose increases with decreasing size of bacteria (12). The slime mold, *physarum*, was found to grow over a spent glass seed of Rn, to cease growing within 2 cm of 17 mc Rn in a glass seed, and to grow to within 3-4 mm of 19 mc Rn in a gold seed (13), showing the greater effect of  $\beta$  radiation on the slime mold. Petrova (14) subjecting cultures of the alga, *zygnema*, to the  $\alpha$  radiation from Po with the extent of radiations to various parts of the cell controlled by filters found that the nucleus was about 700 times more sensitive to irradiation than the cytoplasm. Certain of the simple organisms have been shown to take up some of the elements under discussion. *E. coli* assimilated ThX and when carefully washed bacteria containing the material were plated, the radioactivity spread with the growing colony (15). Hoffman (16) has shown that fresh-water algae accumulate U from water with a concentration of  $10^{-6}$   $\mu\text{gm U/l}$ . The algae subsequent to this treatment contained  $9.1 \times 10^{-4}\%$  U in the ash. It has also been shown that some of the elements or their radiations stimulate various processes in these "simple" organisms. Radiations from Th and U stimulate spore formation and cell vitality of *Bacillus mesentericus* and *bacillus megatherium* (17). In the presence of Rn in porcelain tubes, cultures of *Penicillium notatum* show peak production level of penicillin 2-3 days before cultures without Rn (18). Below the toxic concentration, the presence of U in culture media, stimulates cell division of yeast (19).

#### D. Plants

The first tracer studies with radioactive materials were done by Hevesy (20) with radio-lead in plants. Since that time extensive use has been made

of natural radioelements of which only a brief account can be given here.

The normal concentration of U in plant ash is between  $10^{-3}$  and  $10^{-6}$  gm % (21). The U content of leaves, which is high in relation to that of the rest of the plant, decreases in the fall before the leaves drop. The roots of horsebean plants placed in solutions of RaD (radio-lead) absorb 0.3% from 200 ml. of  $10^{-1}$  N solution and 60% from the same quantity of a  $10^{-6}$  N solution in 24 hours. Transport of lead through the plant is poor, since the leaves contain only about .003 to .03% of the amount in solution (20). Th and U are reported to have a stimulating effect at certain concentrations (22). Gillern has demonstrated that  $\text{Th}(\text{OH})_4$  and  $\text{Th}(\text{NO}_3)_4$  when mixed with soil in a concentration of about 5 mg/kg stimulate the growth of lupine (22), and oats and meadow grass (23). The action is more positive with respect to growth of stem than seed development. Resting seeds of the horse chestnut soaked in solutions of  $\text{UO}_2(\text{NO}_3)_2$  of concentrations of  $10^{-1}$  to  $10^{-5}$  mols/l for 24 hours germinate more rapidly than controls (24). The optimum concentration is dependent on the degree of dormancy; more dormant seeds requiring a higher concentration. Seedlings developing after such treatment contain U in all organs.

### E. Mammals

The description of experiments with the naturally radioactive elements in mammals will be divided according to element. Radium and radon, thorium, polonium, and uranium have been most extensively studied.

#### 1. Radium and Radon

The study of the biological effects of Ra and Rn centered for some time on the toxic effects. The most discussed single group case has been that of the workers in the pitchblende mines of Schneeberg and Joachimsthal who



showed a very high incidence of lung tumors (25). Work with animals exposed to Rn showed that lung adenomas and adenocarcinomas did develop although at a higher air concentration than that to which the men in the mines were exposed (26,27). Despite the difficulties inherent in translating from animal to human data, it seems probable that the Rn concentration of the air in the mines was a factor in the high tumor incidence. It is true, however, that the physical conditions of the work, long hours, excessive dampness, travelling great distances across cold and windy plateaus to and from work, were conducive to respiratory tract irritation and were a predisposing factor in susceptibility to radiation damage. The dangerous effects of radium were not recognized for many years until reports were made of necrosis of the jaw of workers who had absorbed Ra salts (28, 28a). Since that time, the subject of Ra and Rn poisoning has been extensively studied. Although a minute amount of Ra is present in normal human tissues and increases regularly with age (29), very small amounts administered at regular intervals are highly toxic. Rats receiving 40 to 60  $\mu$ g Ra by subcutaneous injection over a period of about 150 days died in about 200 days. The poisoning produced a typical secondary anemia, decalcification of the center portion of all bones and hypercalcification at ends of long bones, hyperplasia of bone marrow, decreased functional ability of the liver, and acute nephritis of the kidney (30). About 25% of the injected Ra was retained and 99% of this was found in the bone. After oral administration, about 7%, and after intradermal, about 50% of the administered Ra was retained, about 90% of that retained being found in the skeleton. In chronic poisoning in humans caused by 1-10  $\mu$ g Ra, 5 - 20 years may pass before development of symptoms with little deviation in the normal blood picture (31). As might be expected from the high concentration of Ra in bone, Ra metabolism is very similar to that

of Ca. The rate of increase of Ca and Ra excretion after establishment of therapy indicates the same efficiency of removal for both materials (32). Transplantable osteogenic sarcomas have been observed in rats fed radium in amounts sufficient to give a retention of 2 ugs Ra after 10 months. The tumors developed in about 365 days and one was maintained for 7 generations with the original high phosphatase level. It is necessary for demonstration of sarcoma formation, that the dose be low enough to allow survival for at least 400 days since this is the latent period of growth (33).

## 2. Thorium

Studies of the effects of thorium have centered principally around the use of thorotrast, colloidal  $\text{ThO}_2$  - a preparation in which Th is in equilibrium with the rest of the series - as a contrast medium in roentgenography of various organs.

After intravenous (34), intracardial (35), and oral (36) administration of thorotrast, the oxide is found principally in the sinusoids of the liver and the capillaries of the spleen. Thorium itself is apparently not excreted although some of the daughters substances are; Th-X is found in the feces, and Tn is exhaled. A major portion of the  $\text{ThO}_2$  injected into two patients 6-7 years prior to measurement was calculated to be still present from data obtained on the Tn content of the breath (34). Thorotrast is also reported to have carcinogenic properties (37). For example, Nattucci and Dall'Armi (38) produced fibrosarcomata in rats after subcutaneous injection and showed severe and diffuse lesions in liver, spleen, and lung of rabbits 1 - 2 years after intravenous injection. Of the remainder of the elements in the series, Th-X (Ra 204), ThB (Pb 212) and ThC (Bi 212) have been investigated to some extent. Th-X was administered to humans in the form of inorganic and organic salts by the intravenous and subcutaneous routes (39).



and by the intravenous route to animals (40). The Th-X content of the blood increased rapidly and then decreased at a fairly rapid rate. As determined in animals, the substance was found mainly in kidney, intestine, and skeleton. From the kidney, only 1% of the injected dose was excreted, while the greater portion of that in the intestine was eliminated in the feces. Th-X in the organic form is more rapidly absorbed by the tissues than in the inorganic form since the absolute activity of the blood following administration is lower while excretion remains the same. Intravenous injection of very small doses of ThB into rabbits gives a marked leucopenia with very slow recovery when it is not fatal. Similar doses of ThC result in a leucocytosis followed by leucopenia which reaches its maximum in 3 - 5 days. The rabbits recover from this in 7 - 11 days after injection. With larger doses, the leucopenia is more pronounced. ThB is deposited in the bone and bone marrow, as might be expected of a lead isotope, while ThC is found mainly in the liver, intestine, and kidneys (41).

### 3. Polonium

Polonium, an element in the uranium series, is excreted after injection into the rabbit by the convoluted tubules of the kidney with the glomeruli playing no direct role. That retained in the body is localized in reticulo-endothelial tissue or interstitial spaces of lymph nodes, bone marrow, spleen, suprarenals, and testicles. When so localized, the irradiation produces destruction of neighboring cells, i.e., lymph or blood elements or seminal cells without harming the reticuloendothelial cells (42). The specific action of Po on the thymo-lymphatic system has been reported by Leblond and Lacassagne (43). In the normal and adrenalectomized rats, Po produced atrophy of the thymus and spleen. With other agents such as cold, trauma, and toxic chemicals, adrenalectomy prevents lymphatic involvement. This is indicative of the direct action of Po on the system concerned.

#### 4. Uranium.

The first member of the uranium series U238 has been shown to occur normally in many living tissues. In mammals, concentrations range from  $2 \times 10^{-9}$  gm U/gm of brain to  $1 \times 10^{-6}$  gm U/gm of hypophysis (44). However a concentration of  $5 \times 10^{-6}$  gm U/gm of body weight is the lethal dose for a dog (45) when the uranium is administered intravenously in the form of nitrate. The lethal dose for other animals, i.e. rabbit and mouse, is of the same order of magnitude. When the uranium is given in the form of colloidal  $\text{UO}_2$ , the lethal dose is more than 10 times as large (46).  $\text{UO}_2(\text{NO}_3)_2$  injected intravenously is removed from the blood rapidly - after 4 hours none remains in the blood, and is eliminated by the kidney (31-88% of injected dose is recovered in the urine in the first 24 hours) (47). The toxicity of uranyl nitrate is due primarily to the destruction caused in the kidney. Secondarily to nephritis, U causes bone lesions of a fibrous, exogenous nature (48). In the kidney, U injected in the form of nitrate is found in the distal convoluted tubules (49) where, with sublethal doses, it so modifies the tubular cells, that they become resistant to toxic doses of  $\text{HgCl}_2$  (50). The nephritis caused by  $\text{UO}_2(\text{NO}_3)_2$  results in such changes as increase in blood  $\text{NH}_3$  (51), decrease in all renal clearances with a negligible change in renal plasma flow (52), decrease in transamination by kidney tissue (53), and a change in the mechanism of elimination of such substances as carmine (54). Sodium citrate in massive doses has been found to protect dogs against lethal doses of  $\text{UO}_2(\text{NO}_3)_2$  (55). The mechanism of this protective action is not known although the maintenance of the "alkali reserve" is not a factor. Another protective substance called "V factor" has been isolated from cultures of diphtheria bacilli. A fraction with similar activity can also be obtained from kidney. "V" factor increases



the excretion rate of U from dogs and protects them against more than twice the lethal dose. It is ineffective in protection of rabbits against U poisoning, and inactive against poisoning by Cr, Hg, Bi, Pb, and benzpyrene in dogs (56).

#### 5. Actinium.

The only member of the actinium series which has been investigated for biological effects to any extent is actino-uranium, U 235. This substance in the form of  $\text{UO}_2$  colloid has been injected into mice and shown to be distributed in a manner similar to other colloids, such as thorotrast. More than 80% of the injected material was localized in the liver and spleen. The primary purpose of this work was to demonstrate the effect of fission in vivo. Therefore, after the animals were injected, they were exposed to a neutron beam. Within six weeks, all those animals so exposed died, while all controls remained alive. It was calculated that the lethal effect of fission recoils is greater than that of a physically equivalent dose of  $\beta$  radiation from  $\text{P}^{32}$  (58).

## References

2. Breger, I. A., and Burton, V. L., Jour. Am. Chem. Soc., 68, 1639 (1946)
3. Fricke, R. E., Cold Spring Harbor Symp. Quant. Biol., 6, 164 (1938)
4. Khenokh, M. A., J. Gen. Chem., (U.S.S.R.) 11, 776 (1941)
5. Dunlap, C. E., and Robbins, F. C., Am. J. Roentgenol., 50, 641 (1943)
6. Veroni, G., and Pirone-Naconetschni, A., Tumori, 17, 51 (1943)
7. Bonet-Maury, P., and Bulgakov, N. I., Comp. rend. soc. biol., 138, 499  
(1944)
8. Bonet-Maury, P., and Perault, R., Comp. rend. soc. biol., 135, 1117 (1941)
9. Lea, D. E., and Salaman, M. H., Brit. Jour. Exp. Path., 23, 27 (1942)
10. Lea, D. E., Smith, K.M., Holmes, B., and Markham, R., Parasitology, 36,  
110 (1944)
11. Levaditi, C., and Noury, H., Comp. rend. soc. biol., 138, 185 (1944)
12. Lea, D. E., "Actions of Radiations on Living Cells", McMillan Co. (1947)
13. Warren, S., and Scott, O. K., Proc. Soc. Exp. Biol. Med., 52, 149 (1943)
14. Petrova, J., Botan. Centr. Abt. A. Beih., 61, 399 (1942)
15. Mallet, L., Jour. de Radiol. et d'electrol., 26, 4, (1944-45)
16. Hoffmann, Josef, Naturwissenschaften, 29, 403 (1941)
17. Cicconi, M., Zentr. Bukt. Parasitenk., 1 abt., 150, 263 (1943)
18. Jahiel, R., Guberman, E., and Kazdan, R., Science, 100, 298 (1944)
19. Hoffmann, Josef., and Garzuly-Janke, R., Bio. Zeit., 313, 372 (1943)
20. Hevesy, G., Biochem. Jour., 17, 439 (1923)
21. Hoffmann, Josef, Bodenkunde u. Pflanzenernahr., 32, 295 (1943)
22. Gillern, C., J. Landw., 89, 223 (1943)
23. Gillern, C., Bodenkunde u. Pflanzenernehr., 27, 197 (1942)
24. Retovsky, R., Ber. deut. botan. Ges., 60, 355 (1942)
25. Lorenz, E., J. Nat. Cancer Inst., 5, 1 (1944)
26. Evans, R. D., J. Ind. Hyg. and Toxicol., 25, 253 (1943)



27. Schraub, A., and Kahlav, G., *Naturwissenschaften*, 31, 170, (1943)
28. Castle, W. B., Drinker, K. R., and Drinker, C. K., *J. Ind. Hygiene*, 7, 371 (1925)
- 28a. Martland, H. S., *J. Am. Med. Assoc.*, 85, 1769 (1925)
29. Krebs, A., *Z. Alterforsch.*, 4, 53 (1942)
30. Thomas, H. E., and Bruner, F. H., *Am. Jour. Roentgenol.*, 29, 641 (1933)
31. Evans, R. D., Harris, R. S., and Bunker, J. W. M., *Am. Jour. Roentgenol.*, 52, 353 (1944)
32. Aub, J. C., Evans, R. D., Gallagher, G. M., and Tibbets, D. M., *Ann. Int. Med.*, 11, 1443 (1938)
33. Dunlap, C. E., Aub, J. C., Evans, R. D., and Harris, R. S., *Am. Jour. Pathol.*, 20, 1 (1944)
34. Stentstrom, W., *Radiology*, 37, 698 (1941)
35. Steinberg, B., Walliker, C. T., and Martin, R. A., *Proc. Soc. Exp. Biol. Med.*, 55, 165 (1944)
36. McClure, C. W., Jankelson, I. R., and Osgood, H., *Rev. Gastroenterol.*, 11, 17 (1944)
37. Roussy, G., and Guerin, M., *Presse Med.*, 49, 761 (1941)
38. Natucci, G., and Dall'Armi, G., *Arch. ital. med. sper.*, 4, 591 (1939)
39. Gerlach, J., *Naturwissenschaften*, 29, 300 (1941)
40. Wolf, P. M., and Born, H. J., *Strahlentherapie*, 70, 342 (1941)
41. Deucher, W. G., Leigh-Smith, A., *Schweiz. med. Wochschr.*, 73, 1092 (1943)
42. Lacassagne, A., Lattes, J. S., Lavedon, J., *J. de radiol et c'electrol.*, 9, 1, (1925)
43. Leblond, C. P., and Lacassagne, A., *Am. J. Roentgenol.*, 50, 801 (1943)
44. Hoffmann, Josef, *Bio. Zeit.*, 315, 26 (1943)
45. Fairhall, L. T., *Physiol. Rev.*, 25, 182 (1945)
46. Weymouth, P. P., and Tobias, C. A., Unpublished data.
47. Holman, R. L., and Douglass, W. A., *Proc. Soc. Exp. Biol. Med.*, 57, 72 (1944)

48. Queloz, M., *Helv. Med. Acta*, 5, 195 (1938)
49. Simonds, J. E., and Hepler, O. E., *Arch. Pathol.*, 39, 103 (1945)
50. McNider, W. D., *Jour. Pharm. and Exp. Therap.*, 73, 58 (1941)
51. Koprowski, H., and Uninski, H., *Rev. brasil. biol.*, 1, 253 (1941)
52. Bobey, M. E., Longley, L. P., Dickes, R., Price, J. W., and Hayman, J. M.  
Jr., *Am. J. Physiol.*, 139, 155 (1943)
53. Vyshepan, E. D., *Biokhimiya*, 8, 45 (1943)
54. Doderio, G., *Riv. patol. sper.*, 30, 21 (1943)
55. Donnelly, G. L., Ross, C. J., Merony, W. H., and Holman, R. L., *Proc.*  
*Soc. Exp. Biol. Med.*, 57, 75 (1944)
56. Vacirca, F., *Zeit. f. physiol. Chem.*, 278, 169 (1943)
58. Tobias, C. A., Weymouth, P. P., and Wasserman, L. R., (in press)



## GENERAL REFERENCES

- Gen 1 Aebersold, P.C. By-products of atomic energy for use by pharmaceutical profession. *Am. J. Pharmacol.* 119: 90-105 1947.
- Gen 2 Allen, A.J., Sampson, M.B., Franklin, R.G. The cyclotron of the biochemical research foundation. *J. Franklin Inst.* 228:5 1939.
- Gen 3 Ambrosen, J., Madsen, B., Ottesen, J., Zerahn, K. Geiger-Muller counter arrangement for biological research. *Acta Physiol. Scand.* 10: 195-213 1945.
- Gen 4 Anonymous. Recent biological studies with radioactive isotopes. *Sci. and Culture* 7: 253-4 1941.
- Gen 5 Anonymous. Therapeutic use of radioactive substances. *J. Am. Med. Assoc.* 121: 54 1943.
- Gen 6 Austregesilo, A. Atomic impact and convulsant therapy of mental diseases. *Cultura Med.* 7: 247-53 1946.
- Gen 7 Bale, W.F. Health protection in production and use of atomic energy. *Occup. Med.* 2: 1-7 1946.
- Gen 8 Barnett, A. The use of radioactive forms of the common elements in physiology. *Physiol. Rev.* 56: 963 1939.
- Gen 9 Baitsell, George A. Science in progress. 322 pp. 1939.
- Gen 10 Beeler, R.C. Radiology in atomic age. *Am. J. Roentgenol.* 56: 683 1946.
- Gen 11 Behounek, F., Novak, F.V. Retention of radioactive substances in body of rats and lethal dose. *Nature* 140: 106 1937.
- Gen 12 Bloch, K. Some aspects of intermediary metabolism. *Currents of Biochemistry.* 1946.

- Gen 13 Bryan, F.A. Radioactive isotopes in medicine. Hygeia 25: 286 1947.
- Gen 14 Buchta, J.W. Radioactive isotopes. West. J. Surg. 54: 467 1946.
- Gen 15 Carlile, T. Review of the use of some radioactive isotopes in medicine. Bull. Clin. 1: 25-37 1947.
- Gen 16 Chadwick, J. The cyclotron and its applications. Nature 142: 630-4 1938.
- Gen 17 Chadwick, J. Atomic energy and medicine (Lloyd Roberts lecture) Brit. Med. J. 1: 263-5 1947.
- Gen 18 Cifarelli, F.P. Medical applications of new nuclear physics. Rev. Med. de Rosario 36: 430-41 1946.
- Gen 19 Copp, H. The role of nuclear physics in medicine and dentistry; applications in medicine. Am. J. Orthodontics 33: 102 1947.
- Gen 20 Copp, H. The role of nuclear physics in medicine and dentistry; The use of radioactive tracers in the study of bones and teeth. Am. J. Orthodontics 33: 109-15 1947.
- Gen 21 Courier, R. Method of radioactive indicators in endocrinology. Arch. Brasil. de Med. 36: 259-64 1946.
- Gen 22 Craver, B.N. Radioactive emanation; their nature, mechanism of action, biologic effects and tolerance limits. J. Indust. Hyg. and Toxicol. 29: 196-200 1947.
- Gen 23 Daniels, F. Plans and problems in nuclear research. Science 104: 91-6 1946.
- Gen 24 De Ment, J. Present and future trends in radiomedicine. West. J. Surg. 55: VIII 1947.



- Gen 25 Dougherty, E.C. Nuclear physics in medicine. This Month in Am. Med. 2: 273-83, 389-95 1947.
- Gen 26 Epifanio, G. Fisica anomica e nucleare in biologia e terapia I neutroni e i corpi beta radioattivi. Coll. Soc. Ital. Biol. Sper. 14: 738-40 1939.
- Gen 27 Epifanio, G. Atomic disintegration in biology and therapy and Institute of Radiology of University of Palermo. Gior. di med. 2: 560-6 1945.
- Gen 28 Evans, Robley, D. Applied nuclear physics. J. App. Physics 12: 260 1941.
- Gen 29 Evans, R.D. Medical applications of Atomic energy. Wien. Med. Wchnschr. 96: 470-2 1946.
- Gen 30 Evelyn, K.A. Physical properties of artifical radio-active isotopes with special reference to their medical applications. McGill M. J. 15: 337-67 1946.
- Gen 31 Failla, G. Nuclear physics and medical research. J. Lancet 67: 68 1947.
- Gen 32 Farre, A. Atomic energy in clinical and therapeutic future. Dia. Med. 18: 1079-82 1946.
- Gen 33 Fearon, W.R. Biochemistry yesterday and tomorrow. Irish J. Med. Sci. 6th Ser.: 659-69 1946.
- Gen 34 Fenn, L.A. Biology in the world today. 1944.
- Gen 35 Foster, J.S. Cyclotron and its contacts with x-ray and radium therapy. Canad. Med. Assoc. J. 38: 222-6 1938.
- Gen 36 Friedell, H.L. Atomic energy and cancer. Tr. & Stud., Coll. Physicians, 14: 68-72 1946.

- Gen 37 Gaddum, J.H. Use of isotopes in biology. Edinburgh M. J. 53: 284-95 1946.
- Gen 38 Glasser, O. Atomic energy (chronology of discoveries) in medicine. Cleveland Clin. Quart. 14: 7-16 1947.
- Gen 39 Govaerts, J. Les isotopes lourds en biologie (physique nucleaire appliquee). 36 pp. 1945.
- Gen 40 Green, David E. Currents in biochemical research. 1946.
- Gen 41 Hamilton, J.G. The use of radioactive isotopes in biology and medicine. Radiol. 39: 541-72 1942.
- Gen 42 Heinlein, G. Über die Behandlung mit Elektronenstrahlen. Wien. Med. Wchnschr. 88: 1327-9 1938.
- Gen 43 Hodges, F.J. Medical implications of atomic energy. J. Mich. Med. Soc. 45: 1339 1946.
- Gen 44 Kamen, M.D. Radioactive tracers in biology. An introduction to tracer methodology. 281 pp. 1947.
- Gen 45 Krusen, F.H. General medical aspects of atomic energy. Am. J. Pharmacol. 119: 24-35 1947.
- Gen 46 Krusen, F.H. General medical aspects of atomic energy. Hosp. Management 63: 114 1947.
- Gen 47 Lawrence, J.H. The use of isotopes in medical research. J. Am. Med. Assoc. 144: 219-25 1947.
- Gen 48 Mallet, L. Radioactive isotopes in biology and medicine. Paris med. 1: 61-5 1946.
- Gen 49 Mallet, L. Radio-counter for ionizing particles. J. Radiol. et d'Electrol. 27: 359-61 1946.



- Gen 50 Meyerhof, O. Intermediate carbohydrate metabolism. (A Symposium on Respiratory enzymes) 1942.
- Gen 51 Mitchell, J.S. Applications of recent advances in nuclear physics to medicine, with special reference to pile and cyclotron as sources of radioactive isotopes. Brit. J. Radiol. 19: 481-7 1946.
- Gen 52 Ottesen, J. Measurement of minute samples with Geiger-Muller Counter. Acta. Physiol. Scand. 10: 214-7 1945.
- Gen 53 Pagniez, P. Method of radioactive indicators in biology and medicine. Presse Med. 54: 625-6 1946.
- Gen 54 Peirce, C.B. Therapeutic applications of radioactive isotopes. McGill Med. J. 15: 371-87 1946.
- Gen 55 Salter, W.T. Tracer substances in nutrition. Chapter 9 in Dietotherapy.
- Gen 56 Sendroy, J., Jr. Mineral metabolism. Ann. Rev. Biochem. 14: 407-430 1946.
- Gen 57 Strohl, A., Berger, M. Les isotopes radioactifs en biologie. 123 pp. 1946.
- Gen 58 Schoenheimer, R. The dynamic state of body constituents. 81 pp. 1942.
- Gen 59 Schubert, G. Medicine and nuclear physics. Deutsche Med. Wchnschr. 71: 25-9 1946.
- Gen 60 Shiflett, E.L. Trends of irradiation therapy in ophthalmology, laryngology, and with radioactive isotopes, with review of literature. Kentucky Med. J. 45: 154-60 1947.
- Gen 61 Spear, F.G. Medical uses of cyclotron. Smithsonian Inst., Annual Rep. (1945) pp. 137-51 1946.

- Gen 62     Strajman, E. Small mica window Geiger-Müller counter for measurements of radioactive isotopes in vivo. Rev. Scient. Inst. 17: 232-5 1946.
- Gen 63     Thomson, D.L. The use of radioactive isotopes as tracers in metabolism. McGill Med. J. 15: 391-7 1946.
- Gen 64     Warren, S. Physiologic reaction to radioactive isotopes. J. Lancet 67: 69-70 1947.

Addendum

- Gen 65     Hevesy, G. The application of isotopic indicators in biological research. Enzymologia 5:138-57 1939.
- Gen 66     Hevesy, G. Application of radioactive indicators in biology. Ann. Rev. Biochem. 9:641-62 1946.



## AMERICIUM

Am 1      Hamilton, J. G. The metabolism of the fission products  
and the heaviest elements. Radiology 49: 325-43, 1947.

# ANTIMONY

- Sb 1 Brady, F. J., Lawton, A. H., Cowie, D. B., Andrews, L. L., Ness, A. T., Ogden, G. E. Localization of trivalent radioactive antimony following intravenous administration to dogs infected with Dirofilaria immitis. Am. J. Trop. Med. 25:103-107 1945.
- Sb 2 Cowie, D. B., Lawton, A. H., Ness, A. T., Brady, F. J., Ogden, G. E. Localization of radioactive antimony following multiple daily injections to a dog infected with Dirofilaria immitis. J. Wash. Acad. Sci. 35:192-195 1945.
- Sb 3 Hallman, L. F., Spear, C. J., and Cowie, D. B. Quantitative analyses of antimony. I. Evaluation of Maren's modification of Webster's rhodamine-B method by means of radioantimony. Naval Med. Res. Inst. Res. Proj. X-514 Report No. 1, pp 1-4, April 1945.
- Sb 4 Hallman, L. F., Strane, J. C., Evans, R. L., and Gordon, L. H. Biological studies of antimony compounds containing radioactive isotopes: evaluation of the rhodamine-B method for the assay of antimony in biological samples. Naval Med. Res. Inst., Res. Proj. X-514 Report No. 2, pp. 1-10, Feb. 1946.
- Sb 5 Smith, R. E., Cowie, D. B., and Hill, C. H. The distribution of radioactive antimony in hamsters infected with Schistosoma mansoni, with particular reference to accumulation in the thyroid. Naval Med. Res. Inst., Res. Proj. X-420 Report No. 1, pp. 1-7, July 1945.
- Sb 6 Smith, R. E., Steele, J. M., Eakin, R. E., Cowie, D. B. Biological studies of antimony compounds containing radioactive isotopes. I. The tissue distribution of antimony inhaled as stibine. Nav. Med. Res. Inst., Res. Proj. X-420 Report No. 2, pp. 1-15, March 1946.



Sb 7 Smith, R. E., Stormont, R. T., Bianco, A. A., Evans, R. L. Biological studies of antimony compounds containing radioactive isotopes. III. The blood-tissue exchange and excretion of antimony in humans given a single dose of tartar emetic. Naval Med. Res. Inst., Res. Proj. X-635 Report No. 1, pp. 1-14, April 1946.

## ARGON

- A 1 Jones, H., Dobson, E., Lawrence, J. Tracer studies of blood-tissue perfusion rates at rest and a new criterion of blood mixing times. Abst. Comm., XVII Internat. Physiol. Cong. pp. 28-9 1947.
- A 2 Lawrence, J. H., Loomis, W.F., Tobias, C.A., Turpin, F.H. Preliminary observations on the narcotic effect of xenon with a review of values for solubilities of gases in water and oils. J. Physiol. 105: 197-204 1946.



## ARSENIC

- As 1 Born, H.J., Timoféeff-Ressovsky, H. Versuche mit radioaktivem Arsen-Isotop an Mäusen. Naturwissenschaften 29: 182-3 1941.
- As 2 du Pont, O., Ariel, I., Warren, S.L. Distribution of radioactive arsenic in normal and tumor-bearing (Brown-Pearce) rabbit. Am. J. Syph., Gonorr. and Ven. Dis. 26: 96-118 1942.
- As 3 du Pont, O., Ariel, I., Warren, S.L. Metabolism of arsenic compounds. J. App. Phys. 12: 324 1941.
- As 4 Hunter, F.T., Kip, A.F. The fate of inorganic arsenic in certain animals and in man. J. App. Phys. 12: 324 1941.
- As 5 Hunter, F.T., Kip, A.F., Irvine, J.W., Jr. Radioactive tracer studies on arsenic injected as potassium arsenite. I. Excretion and localization in tissues. J. Pharmacol. and Exp. Therap. 76: 207-20 1942.
- As 6 Irvine, J.W., Jr. Preparation of radio-arsenic for biological and chemical experiments. J. App. Physics 12: 347
- As 7 Lawton, A.H., Ness, A.T., Brady, F.J., and Cowie, D.B. Distribution of radioactive arsenic following intra-peritoneal injection of sodium arsenite into cotton rats infected with Litomosoides carinii. Science 102: 120-22 1945.
- As 8 Lowry, O.H., Hunter, F.T., Kip, A.F., Irvine, J.W., Jr. Radioactive tracer studies on arsenic injected as potassium arsenite; chemical distribution in tissues. J. Pharmacol. and Exper. Ther. 76: 221-5 1942.
- As 9 Norton, L.B., Hansberry, R. Radioactive tracer methods for determination of the disposition of arsenic in the silkworm. J. Econ.

Entomol. 34: 431-7 1941.



ASTATINE

- At 1     Hamilton, J.G.     The use of radioactive tracers in biology and medicine.     Radiology 39:541-72     1942.
- At 2     Hamilton, J.G., Soley, M.H.     A comparison of the metabolism of iodine and of element 85 (eka-iodine)     Proc. Nat. Acad. Sci.     26:483-9  
1940.

## BARIUM

- Ba 1      Hamilton, J. G.    The metabolism of the fission products and  
the heaviest elements.    Radiology 49: 325-43    1947.



## BISMUTH

- Bi 1 Christiansen, I.A., Hevesy, G., Lomholt, S. Recherches, par un méthode radiochimique, sur la circulation du bismuth dans l'organisme. Comp. Rend. Acad. Sci. 178: 1324-6 1924
- Bi 2 Kroll, H., Arens, R.A., Mesirow, S., Strauss, S.F., Necheles, H. Localization of bismuth in the kidney. Surgery, II. 5: 810-814 1942.

## BORON

- B 1 Krueger, P. G. Some biological effects of nuclear disintegration products on neoplastic tissue. Proc. Nat. Acad. Sci. 26: 181-92, 1940.
- B 2 Zahl, P.A., Cooper, F.S. Localization of lithium in tumor tissue as a basis for slow neutron therapy. Science 93: 64-5, 1943.
- B 3 Zahl, P. A., Cooper, F.S., Dunning, J. R. Some in vivo effects of localized nuclear disintegration products on a transplantable mouse sarcoma. Proc. Nat. Acad. Sci. 26: 589-98, 1940.



## BROMINE

- Br 1 Cope, O., Moore, F.D. A study of capillary permeability in experimental burns and burn shock using radioactive dyes in blood and lymph. *J. Clin. Invest.* 23:241-57 1944.
- Br 2 Eisenman, A.J., Smith, P.K., Winkler, A.W., Elkinton, I.R. The transfer of ions across the stomach wall, studied by means of radioactive isotopes.
- Br 3 Euler, H., Euler, U.S., Hevesy, G. The effect of excitation on nerve permeability. *Acta Physiol. Scand.* 12 (Fasc. 2-3) 1946.
- Br 4 Greenberg, Aird, R.B., Boelter, M.D.D., Campbell, W.W., Cohn, W.E., Murayama, M.M. A study with radioactive isotopes of the permeability of blood-cerebrospinal fluid barrier to ions. *Am. J. Physiol.* 140: 47-64 1944.
- Br 5 Hahn, L., Hevesy, G. Rate of penetration of ions through the capillary wall. *Acta Physiol. Scand.* 1 (Fasc. 4) 1941.
- Br 6 Hamilton, J.G. Rates of absorption of radioactive isotopes of sodium, potassium, chlorine, bromine, and iodine in normal human subjects. *Am. J. Physiol.* 124: 667-8 1938.
- Br 7 Hoagland, D.R., Broyer, T.C., Stout, P.R. Upward movement of salt in the plant, with special reference to metabolic activities of roots. *Science* 91: 454 1940.
- Br 8 Kroll, H., Strauss, S.E., Necheles, H. Concentration and detection of a dye in abscesses. *Proc. Soc. Exper. Biol. and Med.* 43: 228-34 1940.
- Br 9 Kroll, H.H., Strauss, S.F., Necheles, H. Studies on the detection of abscesses and tumors. III. Concentration and detection of a

radioactive substance in abscesses. J. Lab. and Clin. Med. 27:  
50-3 1941.

- Br 10 Moore, F.D., Tobin, L.H. Studies with radioactive di-azo dyes.  
1. The localization of radioactive di-brom trypan blue in inflammatory lesions. J. Clin. Invest. 21: 471-81 1942.
- Br 11 Perlman, I., Morton, M.E., Chaikoff, I.L. The selective uptake of bromine by the thyroid gland with radioactive bromine as indicator. Am. J. Physiol. 134: 107-13 1941.
- Br 12 Peters, H.C. Application of general fluid-circuit theory to absorption from intestine of chloride, bromide, and deuterium oxide. Bull. Math. Biophys. 3: 149-52 1943.
- Br 13 Smith, P.K., Eisenman, A.J., Winkler, A.W. The permeability of human erythrocytes to radioactive chloride, and to bromide and iodide. J. Biol. Chem. 141: 555-61 1941.
- Br 14 Stout, P.R., Applications of radioactive K, Rb, Na, P, and Br to studies of the mineral nutrition of higher plants. J. App. Physics 12: 327 1941.
- Br 15 Tobin, L.H., Moore, F.D. Studies with radioactive di-azo dyes. II. The synthesis and properties of radioactive di-brom trypan blue and radioactive di-brom Evans blue. J. Clin. Invest. 22:155-9 1943.



# CARBON

- C 1 Allen, M.B., Ruben, S. Tracer studies with radioactive carbon and hydrogen. J. Am. Chem. Soc. 64:948-50 1942.
- C 2 Anker, H.S. Synthesis of acetic acid containing isotopic carbon in the methyl group. J. Biol. Chem. 166(1):219-221 1946.
- C 3 Ball, E.G., Tucker, H.F., Solomon, A.K., Vennessland, B. The source of pancreatic juice bicarbonate. J. Biol. Chem. 140:119-29 1941.
- C 4 Barker, H.A., Kamen, M.D. Carbon dioxide utilization in the synthesis of acetic acid by *Clostridium thermoaceticum*. Proc. Natl. Acad. Sci. 31:219-225 August 1945.
- C 5 Barker, H.A., Kamen, M.D., Bornstein, B.T. The synthesis of butyric and caproic acids from ethanol and acetic acid by *Clostridium kluyverium*. Proc. Natl. Acad. Sci. U.S. 31:373-81 1945.
- C 6 Barker, H.A., Kamen, M.D., Haas, V. Carbon dioxide utilization in the synthesis of acetic and butyric acids by *Butyribacterium rettgeri*. Proc. Natl. Acad. Sci., U.S. 31:355-60 1945.
- C 7 Barker, H.A., Ruben, S., Beck, J.V. Radioactive carbon as an indicator of carbon dioxide reduction. IV. The synthesis of acetic acid from carbon dioxide by *Clostridium acidii-urici*. Proc. Natl. Acad. Sci. 26:477-482 1940.
- C 8 Barker, H.A., Ruben, S., Kamen, M.D. The reduction of radioactive carbon dioxide by methane-producing bacteria. Proc. Natl. Acad. Sci. 26:426-430 1940.
- C 9 Bloch, K., Rittenberg, D. An estimation of acetic acid formation in the rat. J. Biol. Chem. 159:45-58 1945.
- C 10 Bloch, K., Rittenberg, D., Sources of acetic acid in the animal body. J. Biol. Chem. 155:243 1944.

- C 11 Bloom, W., Curtis, H.J., McLean, F.C. The deposition of  $C^{14}$  in bone. Science 105(2715):45 1947.
- C 12 Boxer, G.E., Stetten, Jr., Dew. Studies in carbohydrate metabolism. II. The glycogenic response to glucose and lactate in the previously fasted rat. J. Biol. Chem. 155:237-242 1944.
- C 13 Brown, R.W., Wood, H.G., Werkman, C.H. Fixation of carbon dioxide in lactic acid by clostridium butylicum. Arch. Biochem. 5:423-433 1944.
- C 14 Buchanan, J.M. Glycogen formation. Thesis, Harvard Univ., 1943.
- C 15 Buchanan, J.M., Hastings, A.B. The use of isotopically marked carbon in the study of intermediary metabolism. Physiol. Rev. 26: 120-55 1946.
- C16 Buchanan, J.M., Hastings, A.B., Nesbett, F.B. Glycogen formation from pyruvate in vitro in the presence of radioactive carbon dioxide. J. Biol. Chem., 145:715-16 1942.
- C 17 Buchanan, J.M., Hastings, A.B., Nesbett, F.B. The role of carboxyl-labeled acetic, propionic, and butyric acids in liver glycogen formation. J. Biol. Chem. 150:413-425 1943.
- C 18 Buchanan, J.M., Sakami, W., Gurin, S., Wilson, D.W. A study of the intermediates of acetoacetic oxidation with isotopic carbon. J. Biol. Chem. 157:747-8 1945.
- C 19 Buchanan, J.M., Sakami, Warwick, Gurin, Samuel, Wilson, D. Wright. A study of the intermediates of acetate and acetoacetate oxidation with isotopic carbon. J. Biol. Chem. 159:695-709 1945.
- C 20 Buchanan, J.M., Sonne, J.C. The utilization of formate in uric acid synthesis. J. Biol. Chem. 166:781 December 1946.



- C 21 Carson, S.F. The role of carbon dioxide in cellular metabolism. Thesis, Stanford Univ., 1941.
- C 22 Carson, S.F., Foster, J.W., Ruben, S., Barker, H.A. Radioactive carbon as an indicator of carbon dioxide utilization. V. Studies on the propionic acid bacteria. Proc. Natl. Acad. Sci. 27:229-235 1941
- C 23 Carson, S.F., Foster, J.W., Ruben, S., Kamen, M.D. Radioactive carbon as a tracer in the synthesis of propionic acid from CO<sub>2</sub> by the propionic acid bacteria. Science 92:433-34 1940.
- C 24 Carson, S.F., Ruben, S. Carbon dioxide assimilation by propionic acid bacteria studied by the use of radioactive carbon. Proc. Natl. Acad. Sci. 26:422 1940.
- C 25 Carson, S.F., Ruben, S., Kamen, M.D., Foster, J.W. Radioactive carbon di-oxide utilization. VI. The possibility of carbon dioxide reduction via the carboxylase system. Proc. Natl. Acad. Sci. U.S. 27:475-80 1941.
- C 26 Chargaff, E. Note on the mechanism of conversion of  $\beta$ -glycerophosphoric acid into the  $\alpha$ -form. J. Biol. Chem. 144:455 1942.
- C 27 Cohn, W.E., Brues, A.M. Metabolism of tissue cultures III. A method for measuring the permeability of tissue cells to solutes. J. of Gen Physiol. 28:449-461 1944.
- C 28 Committee on Growth Symposium on the use of isotopes in biological research. March 3 and 4, 1947.
- C 29 Conant, J.B., and others. Metabolism of lactic acid containing radioactive carboxyl carbon. J. Biol. Chem. 137:557-66 1941.
- C 30 Cramer, R.D., Kistiakowsky, A.B. The synthesis of radioactive lactic acid. J. Biol. Chem. 137:549-555 1941.

- C 31 Delluva, A.M., D.W. Wilson, A study with isotopic carbon of the assimilation of carbon dioxide in the rat. J. Biol. Chem. 166(2): 739-746 1946.
- C 32 Evans, E.A., Jr. Carbohydrate Metabolism. Ann. Rev. of Biochem. XIII:187-210 1944.
- C 33 Evans, E.A., Jr. The fixation of  $\text{CO}_2$  by animal tissues. The Harvey Lecture Series 39:273-287 1943-44.
- C 34 Evans, E.A., Jr. Pyruvate oxidation and the citric acid cycle. Bull. Johns Hopkins Hosp. 69:225 1941.
- C 35 Evans, E.A., Jr. A symposium on respiratory enzymes. Madison, Wis. 197, 1942.
- C 36 Evans, E.A., Slotin, L.  $\text{CO}_2$  utilization by pigeon liver. J. Biol. Chem. 141:439-450 1941.
- C 37 Evans, E.A., Jr., Slotin, L. The role of carbon dioxide in the synthesis of urea in rat liver slices. J. Biol. Chem. 136:805-806 1940.
- C 38 Evans, E.A., Slotin, L. The utilization of carbon dioxide in the synthesis of  $\alpha$ -ketoglutaric acid. J. Biol. Chem. 136:301-2 1940.
- C 39 Evans, E.A., Slotin, L., Vennesland, B.  $\text{CO}_2$  assimilation in cell-free liver extracts. J. Biol. Chem. 143:565 1942.
- C 40 Evans, E.A., Vennesland, B., Slotin, L. The mechanism of carbon dioxide fixation in cell-free extracts of pigeon livers. J. Biol. Chem. 147:771-84 1943.
- C 41 Foster, J.W., Carson, S.F., Ruben, S., Kamen, M.D. Radioactive carbon as an indicator of carbon dioxide utilization. VII. The assimilation of carbon dioxide by molds. Proc. Natl. Acad. Sci. U.S. 27:590-6 1941.



- C 42 Frenkel, A.W.      Photosynthesis with radioactive carbon, and the distribution of the intermediate products in the plant cells. *Plant Physiol.* 16:654-5 1943.
- C 43 Gross, N.H., Wood, H.G., Werkman, C.H.      Fixation of heavy carbon acetaldehyde by active juices. *J. Bact.* 44:257 1942.
- C 44 Grosse, A.V., Synder, J.C.      Radiographs with  $C^{14}$ . *Science* 105:240-241 February 28, 1947.
- C 45 Hamilton, J.G.      The use of radioactive tracers in biology and medicine. *Radiology* 39:541-72 1942.
- C 46 Hastings, A.B., Buchanan, J.M.      The role of intracellular cations on liver glycogen formation in vitro. *Proc. Nat. Acad. Sci.* 28:473-482 1942.
- C 47 Hastings, A.B., Kistiakowsky, G.B.      Biological studies with radioactive carbon. *J. App. Physics* 12:322 1941.
- C 48 Hastings, A.B., Kistiakowsky, G.B., Cramer, R.D., Klemperer, F.W., Solomon, A.K., Vennesland, B.      Liver glycogen from lactic acid containing radioactive carboxyl carbon. *Science* 91:421 1940.
- C 49 Kalnitsky, G., Werkman, C.H.      The anaerobic dissimilation of pyruvate by a cell-free extract of *Escherichia coli*. *Arch. Biochem.* 2:113-124 1943.
- C 50 Kalnitsky, G., Wood, H.G., Werkman, C.H.       $CO_2$ -Fixation and Succinic Acid Formation by a cell-free enzyme preparation of *Escherichia coli*. *Arch. Biochem.* 2:269-281 1943.
- C 51 Kamen, M.D.      Survey of contemporary knowledge of biogeochemistry *Bull. Am. Museum of Natural History* 87:105-138 1946.
- C 52 Kamen, M.D., Ruben, S.      Studies in photosynthesis with radio-carbon. *J. App. Physics* 12:326 1941.

- C 53 Kamen, M.D., Ruben, S. Synthesis *in vivo* of organic molecules containing radioactive carbon. J. App. Physics 12:310 1941.
- C 54 Kilmer, G.W., Vigneaud, V. du A synthesis of methionine containing isotopic carbon and sulfur. J. Biol. Chem. 154:247-253 1944.
- C 55 Kleinzeller, A. Oxidation of acetic acid in animal tissue. Biochem J. 37:674-78 1943.
- C 56 Krampitz, L.O., Werkman, C.H. The enzymic decarboxylation of oxalacetate. Biochem.J. 35:595 1941.
- C 57 Krampitz, L.O., Wood, H.G., Werkman, C.H. Enzymatic fixation of carbon dioxide in oxalacetate. J. Biol. Chem. 147:243-253 1943.
- C 58 Krebs, H.A. CO<sub>2</sub> assimilation in heterotrophic organisms. Ann.Rev Biochem. 12:529-50. 1943.
- C 59 Krebs, H.A. Intermediary stages in biological oxidation of carbohydrate. Adv. in Enzymol. 3:191-252 1943.
- C 60 Lawrence, J.H., Tobias, C.A. Is CO oxidized to CO<sub>2</sub> in the human body? Air Surgeon's Bull. 2:452-453 1945.
- C 61 Lifson, N., Lorber, V., Wood, H.G. Position of carboxyl carbon of fed acetic acid in glucose from rat liver glycogen. Federation Proc 4:47 1945.
- C 62 Lorber, V., Hemingway, A., Assimilation of CO<sub>2</sub> by the isolated mammalian heart. J. Biol. Chem. 151:647-50, December 1943.
- C 63 Lorber, Victor, Lifson, Nathan, Wood, H.G. Incorporation of acetate carbon into rat liver glycogen by pathways other than carbon dioxide fixation. J. Biol. Chem. 161:411-2, November 1945.
- C 64 Lorber, V., Lifson, N., Wood, H.G., Bancroft, J. The metabolism of acetate by the completely isolated mammalian heart investigated with carboxyl-labeled acetate. Am.J.Physiol. 145:557-60 February 1946.



- C 65 Lorber, V., Olsen, N.S. Metabolism of glycine by the completely isolated mammalian heart investigated with carboxyl-labeled glycine. Proc. Soc. Exptl. Biol. Med. 61:227-9 1946.
- C 66 Medes, G., Floyd, N.F., Weinhouse, S. Fatty acid metabolism. IV. Ketone bodies as intermediates of acetate oxidation in animal tissues J. Biol. Chem. 162:1-9 January 1946.
- C 67 Medes, G., Weinhouse, S., Floyd, N.F. Fatty acid metabolism. II. The breakdown of carboxyl-labeled butyric acid by liver tissue. J. Biol. Chem. 157:35-41 1945.
- C 68 Medes, G., Weinhouse, S., Floyd, N.F. Ketone-body formation from acetate in kidney, with isotopic C as a tracer. J. Biol. Chem. 157:751-2 1945.
- C 69 Miller, Warren W. High efficiency counting of long-lived radioactive carbon as  $\text{CO}_2$ . Science 105(2718):123-125 1947.
- C 70 Mills, G.A., Urey, H.C. The kinetics of isotopic exchange between carbon dioxide, bicarbonate ion, carbonate ion and water. J. Am. Chem. Soc. 62:1019-26 1940.
- C 71 Mouler, J.W., Vennesland, B., Evans, E.A. Jr. A study of enzymatic reactions catalyzed by pigeon liver extracts. J. Biol. Chem. 160:305 1945.
- C 72 Murphey, B.F., Nier, A.O. Variations in the relative abundance of the carbon isotopes. Phys. Rev. 59:771-2 May 1, 1941.
- C 73 Nahinsky, P., Rice, C.N., Ruben, S., Kamen, M.D. Tracer studies with radioactive carbon. The synthesis and oxidation of several three-carbon acids. J. Am. Chem. Soc. 64:2299-2302 1942.
- C 73 Nahinsky, P., Ruben, S. Tracer studies with radioactive carbon: The oxidation of propionic acid. J. Am. Chem. Soc. 63:2275-6 1941.

- C 74 Nier, A.O., Bardeen, J. The production of concentrated carbon ( $^{13}$ ) by thermal diffusion. J. Chem. Phys. 9:690-92 September 1941.
- C 75 Nier, A.O., Gulbransen, E. Variations in the relative abundances of the carbon isotopes. J. Am. Chem. Soc. 61:697-698 1939.
- C 76 Nishina, Y., Endo, S., Nakayama, H. The bacterial synthesis of some dicarboxylic acids with the help of radioactive carbon dioxide. Sci. Papers Inst. Phys. Chem. Research (Tokyo) 38:341-6 1941.
- C 77 Olsen, N.S., Hemingway, A., Nier, A.O. The metabolism of glycine. I. Studies with the stable isotope of carbon. J. Biol. Chem. 148: 611-18 1943.
- C 78 Overstreet, R., Ruben, S., Broyer, T.C. The absorption of bicarbonate ion by barley plants as indicated by studies with radioactive carbon. Proc. Natl. Acad. Sci. U.S. 26:688-695 1940.
- C 79 Rabideau, G.S., Burr, G.O. The use of the  $C_{13}$  isotope as a tracer for transport studies in plants. Am. J. Botany 32:349-56 1945.
- C 80 Reid, A.F. and Weil, A.S., Dunning, J.R. Properties and measurement of  $C_{14}$ . Columbia Univ. Pupin Physics Lab. To be published in the Chem. and Eng. News 1946.
- C 81 Reid, J.C. Synthesis of tyrosine labeled with  $C^{14}$ . Science 105:2721-208 1947.
- C 82 Rittenberg, D., Bloch, K. Biological reactions of AcOH. J. Biol. Chem. 157:749-50 1945.
- C 83 Rittenberg, D., Bloch, K. The utilization of acetic acid for the synthesis of fatty acids. J. of Biol. Chem. 160:417-424 1945.
- C 84 Rittenberg, D., Shemin, D. Isotope technique in the study of intermediary metabolism. Currents in Biochemical Research 1946.



- C 85 Rittenberg, D., Waelsch, H. The source of carbon for urea formation. J. of Biol. Chem. 136:799-800 1940.
- C 86 Ruben, S., Hassid, W.Z., Kamen, M.D. Radioactive carbon in the study of photosynthesis. J. Am. Chem. Soc. 61:661-663 1939.
- C 87 Ruben, S., Kamen, M.D. Nonphotochemical reduction of CO<sub>2</sub> by biological systems. J. App. Physics 12:321 1941.
- C 88 Ruben, S., Kamen, M.D. Photosynthesis with radioactive carbon. IV. Molecular weight of the intermediate products and a tentative theory of photosynthesis. J. Amer. Chem. Soc. 62:3451-3455.
- C 89 Ruben, S., Kamen, M.D. Production and properties of long-lived carbon. J. App. Physics 12:311 1941.
- C 90 Ruben, S., Kamen, M.D. Radioactive carbon in the study of respiration in heterotrophic systems. Proc. Natl. Acad. Sci. U.S. 26:418-22 1940.
- C 91 Ruben, S., Kamen, M.D., Hassid, W.Z. Photosynthesis with radioactive carbon. II. Chemical properties of the intermediates. J. Amer. Chem. Soc. 62:3443-3450. 1940.
- C 92 Ruben, S., Kamen, M.D., Hassid, W.Z., DeVault, D.C. Photosynthesis with radio-carbon. Science 90:570-571 1939.
- C 93 Ruben, S., Kamen, M.D., Perry, L.H. Photosynthesis with radioactive carbon III. Ultracentrifugation of intermediate products. J. Am. Chem. Soc. 62:3450 1940.
- C 94 Sakami, W., Evans, W.E., Gurin, S. Methods of synthesis of organic compounds labeled with C<sup>13</sup> 1. Acetate, Acetoacetate, Pyruvate and Glycine. Department of Physiol. Chem. School of Me. Univ. of Pa.
- C 95 Shemin, David. The biological conversion of l-serine to glycine. J. Biol. Chem. 162:297-307 1946.

- C 96 Slade, H.D., Werkman, C.H. Assimilation of acetic and succinic acids containing heavy carbon by aerobacter indologenes. Arch. Biochem. 2:97-111 1943.
- C 97 Slade, H.D., Werkman, C.H. Assimilated of acetic and succinic acids containing heavy carbon by aerobacter indologenes. Proc. Soc. Exptl. Biol. Med. 51:65-66 1942.
- C 98 Slade, H.D., Werkman, C.H. The mechanism of anerobic citrate dissimilation by all suspensions of Streptococcus paracitrovorus. J. Bact. 41:3-4 1940.
- C 99 Slade, H.D., Wood, H.G., Nier, A.O., Hemingway, A., Werkman, C.H. Assimilation of heavy carbon dioxide by heterotrophic bacteria. J. Biol. Chem. 143:133-145 March, 1942.
- C 100 Slade, H.D., Wood, H.G., Nier, A.O., Hemingway, A., Werkman, C.H. Note on the utilization of carbon dioxide by heterotrophic bacteria. Ia. State Coll. J. Sci. 15:339-341 1941.
- C 101 Smith, H.C., Cowie, D.B. Absorption and utilization of radioactive carbon dioxide by sunflower leaves. Plant Physiol. 16:257-71 1941.
- C 102 Smith, J.H.C., Cowie, Dean B. The measurement of artificial radioactivity in liquid tracer samples using  $C^{11}$ . J. Appl. Physics 12:78-82 January 1941.
- C 103 Solomon, A.K., Vennesland, B., Klemperer, F.W., Buchanan, J.M., Hastings, A.B. The participation of carbon dioxide in the carbohydrate cycle. J. Biol. Chem. 140:171-182 1941.
- C 104 Sonne, J.C., Buchanan, J.M., Delluva, A.M. Biological precursors of uric acid carbon. J. Biol. Chem. 166(1):395-396 1946.



- C 105 Swenseid, M.E. The use of the stable isotope, heavy carbon, in study of intermediary metabolism. Ph.D. thesis, Univ. of Minn.
- C 106 Swenseid, M.E., Barnes, R.H., Hemingway, A., Nier, A.O. The formation of acetone bodies from acetic acid. J. Biol. Chem. 142:47-52 Jan 1942.
- C 107 Tobias, C.A., Lawrence, J.H., Roughton, F.J.W., Root, W.S., Gregersen, M.I. The elimination of carbon monoxide from the human body with reference to the possible conversion of carbon monoxide to carbon dioxide. Am. J. Physiol. 145:253-63 1945.
- C 108 Tobias, C., Segre, E. High Energy Carbon Nuclei The physical Rev. 70:89 1946.
- C 109 Utter, M.F., Krampitz, L.O., Werkman, C.H. Oxidation of acetyl phosphate and other substrates by micrococcus lysodeikticus. Arch. Biochem. 9:285-300 1946.
- C 110 Utter, M.F., Lipmann, F., Werkman, C.H. Reversibility of the phosphoroclastic split of pyruvate. J. Biol. Chem. 158:521-531 (1945).
- C 111 Utter, M.F., Werkman, C.H., Lipmann, F. Reversibility of the phosphoroclastic split of pyruvate. J. Biol. Chem. 154:723-24 1944.
- C 112 Utter, M.F., Wood, Harland, G. Fixation of carbon dioxide in oxalacetate by pigeon liver. J. Biol. Chem. 160:375-6 Sept. 1945.
- C 113 Van Niel, C.B., Ruben, S., Carson, S.F., Kamen, M.D., Foster, J.W. Radioactive carbon as an indicator of carbon dioxide utilization. VIII. Role of carbon dioxide in cellular metabolism. Proc. Natl. Acad. Sci. U.S. 28:8-15 1942.
- C 114 Van Niel, C.B., Thomas, J.O., Ruben, S., Kamen, M.D. Radioactive carbon as an indicator of carbon dioxide utilization IX. The assimilation of carbon dioxide by Protozoa. Proc. Natl. Acad. Sci. U.S. 28:157 1942.

- C 115 Vennesland, B., Solomon, A.K., Buchanan, J.M., Cramer, R.D., Hastings, A.B. Metabolism of lactic acid containing radioactive carbon in the alpha and beta position. J. Biol. Chem. 142:371 1941.
- C 116 Vennesland, B., Solomon, A.K., Buchanan, J.M., Hastings, A.B. Glycogen formation from glucose in presence of radioactive carbon dioxide. J. Biol. Chem. 142:379-86 1942.
- C 117 Vigneaud, V. Du, Kilmer, G.W., Rachele, J.R., Cohn, M. On the mechanism of the conversion in vivo of methionine to cystine. J. Biol. Chem. 155:645-51 1944.
- C 118 Weinhouse, S., Medes, G., Floyd, N.F. Fatty acid metabolism. V. The conversion of fatty acid intermediates to citrate, studied with the aid of isotopic carbon. J. Biol. Chem. 166:691 Dec. 1946.
- C 119 Weinhouse, S., Medes, G., Floyd, N.F. Fatty acid metabolism. The mechanism of ketone body synthesis from fatty acids, with isotopic carbon as tracer. J. Biol. Chem. 155:143-151 (1944) 143:689 1944.
- C 120 Weinhouse, S., Medes, G., Floyd, N.F. Fatty acid metabolism; III reactions of carboxyl-labeled acetic acid in liver and kidney. J. Biol. Chem. 158:411-419 1945.
- C 121 Weinhouse, S., Medes, G., Floyd, N.F. Ketone body formation from fat acids using heavy C as a tracer. Am. J. Med. Sci. 207:812-813 1944.
- C 122 Weinhouse, Sidney, Medes, Grace, Floyd, N.F., Noda, L. Intermediates of acetate oxidation in the kidney. J. Biol. Chem. 161:745-746 1946.
- C 123 Werkman, C.H., Wood, H.G. Heterotrophic assimilation of carbon dioxide. Adv. in Enzymology 2:135 1942.
- C 124 Wood, H.G. The fixation of CO<sub>2</sub> and the inter-relationships of the tri-carboxylic acid cycle. Phys. Rev., 26:198 1946.



- C 125 Wood, H.G., Brown, R.W., Werkman, C.H. Mechanism of the butyl alcohol fermentation with heavy carbon acetic and butyric acids and acetone. Arch. Biochem. 6:243-260, March 1945.
- C 126 Wood, H.G., Brown, R.W., Werkman, C.H., Stuckwisch, C.G. The degradation of heavy carbon butyric acid from the butyl alcohol fermentation. Amer. Chem. Soc. J. 66:1812-1818 1944.
- C 127 Wood, H.G., Lifson, N., Lorber, V. The position of fixed carbon in glucose from rat liver glycogen. J. Biol. Chem. 159:475-489 1945.
- C 128 Wood, H.G., Vennesland, B., Evans, E.A., Jr. The mechanism of carbon dioxide fixation by cell free extracts of pigeon liver. Distribution of labeled carbon dioxide in the products. J. Biol. Chem. 159:153-158 1945.
- C 129 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Fixation of carbon dioxide by pigeon liver in the dissimilation of pyruvic acid. J. Biol. Chem. 142:31-45 January 1942.
- C 130 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Heavy carbon as a tracer in bacterial fixation of CO<sub>2</sub>. J. Bact. 41:20. 1941.
- C 131 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Heavy carbon as a tracer in bacterial fixation of carbon dioxide. J. Biol. Chem. 135:789-90 1940.
- C 132 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Heavy carbon as a tracer in heterotrophic carbon dioxide assimilation. J. Biol. Chem. 139:365-76 1941.
- C 133 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Note on the degradation of propionic acid synthesized by Propionibacterium. Ia. State Coll. Jour. Sci. 15:213-214 1941.

- C 134 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Position of carbon dioxide-carbon in propionic acid synthesized by propionibacterium. *Proc. Soc. Exper. Biol. and Med.* 46:313 1941.
- C 135 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. The position of carbon dioxide carbon in succinic acid synthesized by heterotropic bacteria. *J. Biol. Chem.* 139:377-381 1941.
- C 136 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Heavy carbon as a tracer in heterotropic carbon dioxide assimilation. *J. Biol. Chem.* 139:365 1941.
- C 137 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O. Mechanism of fixation of carbon dioxide in the Krebs cycle. *J. Biol. Chem.* 139:483 1941; 142:31 1942.
- C 138 Wood, H.G., Werkman, C.H., Hemingway, A., Nier, A.O., Stuckwisch, C.G. Reliability of reactions used to locate assimilated carbon in propionic acid. *J. Am. Chem. Soc.* 63:2140-2 1941.
- C 139 Wood, J.L. and Vigneaud, Vincent du. A new synthesis of cystine. *J. of Biol. Chem.* 131:267 1939.



## CALCIUM

- Ca 1 Armstrong, W. D. Radioactive calcium and phosphorus uptake by calcified tissues. J. Dental Res. 24: 192 1945.
- Ca 2 Campbell, W. W., Greenberg, D. M. Studies in calcium metabolism with aid of its induced radioactive isotope I. Proc. Nat. Acad. Sc. 26: 176-80, 1940.
- Ca 3 Committee on Growth. Symposium on the use of isotopes in biological research. March 3 and 4, 1947 (mimeographed).
- Ca 4 Greenberg, D. M. Tracer studies with radioactive isotopes of the metabolism of calcium and manganese in the animal organism. J. App. Physics 12: 318, 1941.
- Ca 5 Greenberg, D. M. Studies in mineral metabolism with the aid of artificial radioactive isotopes. VIII. Tracer experiments with radioactive calcium and strontium on the mechanism of Vitamin D. action in rachitic rats. J. Biol. Chem. 157: 99-104, 1945.
- Ca 6 Greenberg, D. M., Troescher, F. M. Studies with radioactive isotopes of calcium and strontium by way of bile. Proc. Soc. Exper. Biol. and Med. 49: 488-91, 1942.
- Ca 7 Hamilton, J. G. The use of radioactive tracers in biology and medicine. Radiology 39: 541-72, 1942.
- Ca 8 Pecher, C. Biological investigations with radioactive calcium and strontium. Proc. Soc. Exper. Biol. and Med. 46: 86-90, 1941.
- Ca 9 Pecher, C. Biological investigations with radioactive calcium and strontium. Preliminary report on the use of radioactive strontium in the treatment of metastatic bone cancer. Univ. Calif. Publ. Pharmacol. 2: 117-150, 1942.

- Ca 10 Pecher, C., Pecher, J. Radiocalcium and radiostrontium metabolism in pregnant mice. Proc. Soc. Exper. Biol. and Med. 46: 91-94, 1941.
- Ca 11 Reed, C. I. Metabolism of calcium and phosphorus. Rev. Argentino-Norteamer. Cienc. Med. (Buenos Aires) 1: 695-705, 1946.
- Ca 12 Walke, H., Thompson, F. C., Holt, J. The Radioactive isotopes of calcium and their suitability as indicators in biological investigations. Phys. Rev. 57: 177-84, 1940.



CERTUM

- Ce 1 Copp, D.H., Axelrod, D.J., Hamilton, J.G. The deposition of radioactive metals in bone as a potential health hazard. Am. J. Roentgenol. and Rad. Ther. 58: 10-16 1947
- Ce 2 Hamilton, J.G. The metabolism of the fission products and the heaviest elements. Radiol. 48: 325-43 1947.
- Ce 3 Lisco, H., Finkel, M.P., Brues, A.M. Carcinogenic properties of radioactive fission products and of plutonium. Radiol. 58: 361-3 1947.

## CESIUM

- Cs 1      Hamilton, J. G.    The metabolism of the fission products  
                                 and the heaviest elements.    Radiology 49: 325-43, 1947.



## CHLORINE

- Cl 1 Born, H. J., Timoféeff-Ressovsky, H. Versuche mit radioaktivem Chlor-Isotop an Mäusen. *Naturwissenschaften* 28:253-254 1940.
- Cl 2 Brunschwig, A., Schmitz, R. L. Rapidity of passage of chloride ion from blood into gastric juice of stimulated stomach. *Proc. Soc. Exper. Biol. and Med.* 43:438-441 1940.
- Cl 3 Brunschwig, A., Schmitz, R., Slotkin, L. The secretion of chlorine ions in achlorhydric gastric juice; observations by means of radioactive chlorine. *Am. J. Digest. Dis.* 8:171-173 1941.
- Cl 4 Eisenman, A. J., Smith, P. K., Winkler, A. W., Elkinton, J. R. The transfer of ions across the stomach wall, studied by means of radioactive isotopes. *J. Biol. Chem. (Proc. Am. Soc. Biol. Chem., 35th Ann. Mtg.)* 140:XXXV 1941.
- Cl 5 Fenn, W. O. The distribution of radioactive potassium, sodium and chlorine in rats and rabbits. *J. App. Phys.* 12:316 1941.
- Cl 6 Hahn, L., Hevesy, G. Rate of penetration of ions through the capillary wall. *Acta Physiol. Scand.* 1:347-361 1941.
- Cl 7 Hamilton, J. G. Rates of absorption of radioactive isotopes of sodium, potassium, chlorine, bromine, and iodine in normal human subjects. *Am. J. Physiol.* 124:667-668 1938.
- Cl 8 Johnston, G. W., Lee, C. O. A radioactive method of testing adsorption from ointment bases. *J. Am. Pharm. Assoc.* 32:278-280 1943.
- Cl 9 Kinsey, V. E., Grant, W. M., Cogan, D. G., Livingood, J. J., Curtis, B. R. Sodium, chloride, and phosphorus movement and the eye. *Arch. Ophthalmol.* 27:1126-1131 1942.
- Cl 10 Lark-Horovitz, K. The intake of radioactive sodium and potassium chloride and the testing of enteric coatings. *J. App. Phys.* 12:317 1941.

- C1 11 Manery, J. F., Haege, L. F. The extent to which radioactive chloride penetrates tissues, and its significance. Am. J. Physiol. 134:83-93 1941.
- C1 12 Peters, H. C. Application of general fluid-circuit theory to absorption from intestine of chloride, bromide, and deuterium oxide. Bull. Math. Biophys. 3:149-152 1943.
- C1 13 Smith, P. K., Eisenman, A. J., Winkler, A. W. The permeability of human erythrocytes to radioactive chloride, and to bromide and iodide. J. Biol. Chem. 141:556-561 1941.
- C1 14 Visscher, M. B., and others. Isotopic tracer studies on the movement of water and ions between intestinal lumen and blood. Am. J. Physiol. 142:550-575 1944.
- C1 15 Winkler, A. W., Elkinton, J. R., Eisenman, A. J. Comparison of sulfocyanate with radioactive chloride and sodium in measurement of extracellular fluid. Am. J. Physiol. 139:239-246 1943.



## COBALT

- Co 1 Copp, D. H., Greenberg, D. M. Studies in mineral metabolism with the aid of artificial radioactive isotopes; VI. Cobalt. Proc. Nat. Acad. Sci. 27:153-157 1941.
- Co 2 Frost, D. V., Spitzer, E. H., Elvehjem, C. A., Hart, E. B. Some effects of cobalt and liver substance on blood building in dogs. Am. J. Physiol. 134:746 1941.
- Co 3 Greenberg, D. M., Copp, D. H., Cuthbertson, E. M. Studies in mineral metabolism with the aid of artificial radioactive isotopes. VII. Distribution and excretion, particularly by way of the bile, of iron, cobalt, and manganese. J. Biol. Chem. 147:749-756 1943.
- Co 4 Sheline, G. E., Chaikoff, I. L., Montgomery, M. L. The elimination of administered cobalt in pancreatic juice and bile of the dog, as measured with its radioactive isotopes. Am. J. Physiol. 145:285-290 1946.

## COLUMBIUM

- Cb 1 Dobson, E., Kelly, L., Jones, H., Gofman, J. Personal communication (see Zr 2).
- Cb 2 Hamilton, J. G. The metabolism of the fission products and the heaviest elements. Radiol. 48: 325-43 1947.



## COPPER

- Cu 1 Mazia, D., Mullins, L. J. Radioactive copper and the mechanism of oligodynamic action. *Nature* 147:642 1941.
- Cu 2 Schubert, G., Vogt, H., Maurer, W., Riezler, W. Tierexperimentelle Indikatoruntersuchungen mit radioaktivem Kupfer. *Naturwissenschaften* 31:589-590 1943.
- Cu 3 Schultze, M. O., Simmons, S. J. The use of radioactive copper in studies on nutritional anemia of rats. *J. Biol. Chem.* 142:97-106 1942.
- Cu 4 Schultze, M. O., Simmons, S. J. Studies with radioactive copper. *J. App. Phys.* 12:315 1941.
- Cu 5 Yoshikawa, H., Hahn, P. F., Bale, W. F. Form of combination of radioactive iron and copper in plasma following ingestion. *Proc. Soc. Exper. Biol. and Med.* 49:285-289 1942.
- Cu 6 Yoshikawa, H., Hahn, P. F., Bale, W. F. Red cell and plasma radioactive copper in normal and anemic dogs. *J. Exper. Med.* 75:489-494 1942.

## CURIUM

- Cm 1      Hamilton, J. G. The metabolism of the fission products  
and the heaviest elements. Radiology 49:325-43, 1947.



# DEUTERIUM

- D1 Anchel, M. Schoenheimer, R. Deuterium as indicator in study of intermediary metabolism; XV further studies in coprosterol formation. Use of compounds containing labile deuterium for biological experiments. J. Biol. Chem. 125:23-31 1938.
- D2 Anderson, R.S., Harvey, E.N. The effect of deuterium oxide on the luminescence of luciferin. J. Cell. and Comp. Physiol. 5:249-253 1934.
- D3 Austoni, M. Ricerche sperimentali sull 'azione dell'acqua pesante ( $D_2O$ ) sulla riserva alcalina. Policlinico (sez.med.) 45:217-29 1938
- D4 Bach, S.J. Biological methylation. Biol. Rev. Cambridge Phil. 20:158-175 1945.
- D5 Barbour, H.G. Effects of heavy water on mammalian metabolism. Proc. Soc. Exp. Biol. and Med. 32:1365 1935.
- D6 Barbour, H.G. Basis of Pharmacological action of heavy water in mammals. Yale J. Biol. and Med. 9:551-65 1937.
- D7 Barbour, H.G. Effects of heavy water on living cells. Science 86:587-8 1937.
- D8 Barbour, H.G., Allen, E. Tumor growth in mice, 1/5 saturated with deuterium oxide (heavy water). Am. J. Cancer 32:440-6 1938.
- D9 Barbour, H.G., Bogdanovitch, S.B. Pharmacology of deuterium oxide; II evidence from fish melanophores for sympathomimetic action. J. Pharmacol. and Exper. Ther. 61:148-52 1937.
- D10 Barbour, H.G., Dickerson, V.C. Pharmacological action of deuterium oxide; VII its effect on hydrolysis of acetylcholine. J. Pharmacol. and Exper. Ther. 65:281-6 1939.
- D11 Barbour, H.G., Hammett, F.S. Heavy water and longevity Sci. 90:538-9 1939.

- D12 Barbour, H.G., Herrmann, J.B. Pharmacological action of deuterium oxide; IV sympathomimetic action of deuterium oxide in mice. J. Pharmacol. and Exper. Ther. 62:158-64 1938.
- D13 Barbour, H.G., Rice, L.E. Pharmacological action of deuterium oxide; V calorogenic saturation level and influence of ergotoxine. J. Pharmacol. and Exper. Ther. 62:292-300 1938.
- D14 Barbour, H.G., Rice, L.E. Pharmacological action of deuterium oxide; VI its influence upon insensible water loss. J. Pharmacol. and Exper. Ther. 62:363-71 1938.
- D15 Barbour, H.G., Trace, J. Pharmacological action of deuterium oxide; I toxicity and symptoms; metabolic rate; water exchanges. J. Pharmacol. and Exper. Therap. 58:460-82 1937.
- D16 Barnes, T.C. Further observations on the physiological effect of the heavy hydrogen isotope in Spirogyra. Am. J. Bot. 20:681 1933
- D17 Barnes, T.C. A possible physiological effect of the heavy hydrogen isotope in water. J. Am. Chem. Soc. 55:4332 1933.
- D18 Barnes, T., Cunliffe. Alleged stimulation of moulds by paraffin in heavy water. Nature (London) 134:573-574 1934.
- D19 Barnes, T., Cunliffe. The effect of heavy water of low concentration on Euglena. Science 79:370 1934.
- D20 Barnes, T.C., Biological effects of water. Yale Sci. Mag. Summer No. 1935.
- D21 Barnes, T.C., Biological effects of heavy water. Am. J. Sci. 30:14 1935.
- D22 Barnes, T., Cunliffe Bioelectrical potential in heavy water. Sci. 83:506 1936.



- D23 Barnes, T.C. Experiments on Ligia Iv. The combined effects of heavy water and temperature. Biol. Bull. 70:109 1936.
- D24 Barnes, T.C. Experiments on Ligia in Bermuda. V. Further effects of salts and of heavy sea water. Biol. Bull. 74:108-116 1938.
- D25 Barnes, T.C. Antagonism between heavy water and adrenalin on the rate and action current of the heart. Anat. Rec. 75:Suppl. 48 1939.
- D26 Barnes, T., Cunliffe. The influence of heavy water and temperature on the electrical potential of frog skin. J. Cell. and Comp. Physiol. 13:39-50 1939.
- D27 Barnes, T.C. Combined effects of heavy water and adrenalin on rate and action current of excised auricles of turtle. Am. J. Physiol. 129:664-71 1940.
- D28 Barnes, T.C. Modifications of social rythms of activity in colonies of ants by heavy water, alcohol and other agents. Anat. Rec. 78:Suppl. 94 1940.
- D29 Barnes, T.C. Rhythms of activity in ant colonies. J. Gen. Psychol. 25:249-255 1941.
- D30 Barnes, T.C., Gaw, H.Z. The chemical basis for some biological effects of heavy water. J. Amer. Chem. Soc. 57:590-591 1935.
- D31 Barnes, T.C., Jahn, T.L. Properties of water of biological interest. Quart. Rev. Biol. 9:292-341 1934.
- D32 Barnes, T.C., Larson, E.J. Further experiments on the physiological effect of heavy water and of ice water. J. Am. Chem. Soc. 55:5059 1933.
- D33 Barnes, T.C., Larson, E.J. The influence of heavy water of low concentration on Spirogyra, Planaria and on enzyme action. Protoplasma. 22:431-443 1934.

- D34 Barnes, T.C., Larson, E.J. Parasitism in heavy water of low concentration. *Nature* 133:873 1934.
- D35 Barnes, T.C., Warren, J. Heart rate in heavy water. *Science* 81:346 1935.
- D36 Barnes, T.C., Warren, J. The combined effects of heavy water and temperature on the heart rate. *Anat. Rec.* 64, Suppl. 1:68 1935.
- D37 Barnes, T.C., Warren, J. The combined effects of heavy water and temperature on the heart-rate of the turtle. *Physiol. Zool.* 10:71-93 1937.
- D38 Barrett, H.M., Best, C.H., Ridout, J.H., A study of the source of liver fat using deuterium as an indicator. *J. Physiol.* 93:367-381 1938.
- D39 Bernhard, K. The fate of alcohol in the animal body. *Z. Physiol-chem.* 267:99-102 1940.
- D40 Bernhard, Karl Source of acetyl groups in vivo. I. Acetylation of sulfanilamide and  $\beta$ -aminobenzoic acid during simultaneous dosage with deuterioacetic acid. *Z. Physiol. Chem.* 267:91-8 1940.
- D41 Bernhard, Karl. Die Bestimmung des Deuteriums in organischen Verbindungen. *Verhandl.d. Vereins d. Schweiz. Physiol.* pp. 4-5 1941.
- D42 Bernhard, Karl. Biological degradation of fat acids through methyl oxidation. Recovery and metabolism of dicarboxylic acids containing deuterium. *Helv. Chim. Acta* 24:1412-25 1941.
- D43 Bernhard, K. Über die Herkunft der Essigsäure bei den Acetylierungen in vivo. II. Fütterung von Sulfanilamid and Deuterio-Bernsteinsäure. *Hoppe-Syler's Zeitschr. Physiol. Chem.* 271:208 1941.
- D44 Bernhard, K., Schoenheimer, R. The inertia of highly unsaturated fatty acids in the animal, investigated with deuterium. *J. Biol. Chem.* 133:707 1941.



- D45 Bernhard, K., Schoenheimer, R., The rate of formation of stearic and palmitic acids in normal mice. *J. Biol. Chem.* 133:713 1941.
- D46 Bernhard, K., Steinhauser, H. Fat metabolism with the aid of D as indicator. III. Lipid synthesis in inanition. *Helv. Chim. Acta.* 27:207-10 1944.
- D47 Bernhard, K., Steinhauser, H., Buller, F. Investigations on fat metabolism with the aid of D as indicator. I The question of the fat acids necessary for life (essential fat acids). *Helv. Chim. Acta.* 25:1313-18 1944.
- D48 Bleakney, W. and Gould, A.J. The relative abundance of hydrogen isotopes. *Phys. Rev.* 44:265 1933.
- D49 Bloch, K. The biological conversion of cholesterol to pregnandiol. *J. Biol. Chem.* 157:661-6 1945.
- D50 Bloch, K., Berg, B.N., Rittenberg, D. The biological conversion of cholesterol to cholic acid. *J. Biol. Chem.* 149:no.2 511-517 1943.
- D51 Bloch, K., Borek, E. Biological acetylation of natural amino acids. *J. Biol. Chem.* 164:483-4 1946.
- D52 Bloch, K., Borek, E., Rittenberg, D. Synthesis of cholesterol in surviving liver. *J. Biol. Chem.* 162:441-9 1946.
- D53 Bloch, K., Rittenberg, D. The biological formation of cholesterol from acetic acid. *J. Biol. Chem.* 143:297-8 1942.
- D54 Bloch, K., Rittenberg, D. On the utilization of acetic acid for cholesterol formation. *J. Biol. Chem.* 145:625-36 1942.
- D55 Bloch, K., Rittenberg, D. The preparation of deuterio cholesterol. *J. Biol. Chem.* 149: no.2; pp. 505-9 1943.
- D56 Bloch, K., Rittenberg, D. An estimation of acetic acid formation in the rat. *J. Biol. Chem.* 159:45-58 1945.

- D57 Bogdanovitch, S.B., Barbour, H.G. The pharmacological action of deuterium oxide. III. Its protective effect on acetyl choline and epinephrine. J. Pharmacol. and Exp. Therap. 62:149-157 1938.
- D58 Bonhoeffer, K.F. Enzyme action in heavy water. Ergebnisse Enzymforsch. 6:47-56 1937.
- D59 Bonhoeffer, K.F. Physiological-chemical investigations with deuterio compounds. Z. Elektrochem. 44:87-98 1938.
- D60 Bonhoeffer, K.F., Salzer, F. Untersuchungen über die fermentative Spaltung von Glucosiden mit schwerem Wasser. Naturwiss. 23:867 1936.
- D61 Borocco, A.L. Deuterium and heavy water. Rev. Chim. Ind. 46:322-9 1937.
- D62 Boxer, G.E., Stetten, DeW., Jr. The role of thiamine in the synthesis of fatty acids from carbohydrate precursors. J. Biol. Chem. 153:607-616 1944.
- D63 Brandt, W. Der "schwere" Wasserstoff und seine biologische Bedeutung. Klin. Wchnschr. 13:1009-1012 1934.
- D64 Brandt, W. Die Glykolyse unter dem Einfluss von Deuteriumoxyd. Klin. Wchnschr. 14:1453 1935.
- D65 Brandt, W. Fortschritte in der Erkenntnis der biologischen Bedeutung des schweren Wasserstoffs. Klin. Wchnschr. 14:521 1935.
- D66 Brandt, W. Der Einfluss von Deuteriumoxyd auf die Aktion des isolierten überlebenden Froschherzens. Klin. Wchnschr. 14:1597-99 1936.
- D67 Brandt, W. The influence of heavy water on the enzymic digestion of urea by urease. Klin. Wochschr. 16:23 1937.
- D68 Brandt, W. Über den Einfluss von schwerem Wasser auf die Harnstoffspaltung durch Urease. Biochem. Ztschr. 291:99-104 1937.



- D69 Brandt, W., Reindell, H. Das Elektrokardiogram des isolierten überlebenden Froschherzens unter dem Einfluss von leichtem und schwerem Wasser. *Klin. Wchnschr.* 15:260-5 1936.
- D70 Breusch, F., Hofer, E. Über das Verhältniss des schweren Wassers zum leichten im Organismus, *Klin. Wchnschr.* 13:1815 1934.
- D71 Brooks, S.C. Permeability of erythrocytes to deuterium oxide (heavy water.) *J. Cell. and Comp. Physiol.* 7:163-171 1936.
- D72 Brooks, S.C. Osmotic effects of deuterium oxide (heavy water) on living cells. *Science* 86:497-8 1937.
- D73 Brown, W.G., Kharasch, M.S., Sprowls, W.R. Exchange reactions in deuterio-alcohol. II. *J. Org. Chem.* 4:442-55 1939.
- D74 Brun, J., Tronstad, L. Some germination experiments with peas in heavy water. *K. Norske Vidensk. Selsk. Forhandl. (Trondheim)* 7 (paper 48):171-173 1935.
- D75 Caldwell, M.L., Doebbeling, S.E. A study of the influence of heavy water upon amylase formation in barley. *J. Biol. Chem.* 123:479-483 1938.
- D76 Caldwell, M.L., Doebbeling, S.E., Van Wicklen, F.C. A study of the influence of heavy water upon the activities and upon the stabilities of the amylases of barley and of malted barley. *J. Amer. Chem. Soc.* 61:125-127 1939.
- D77 Calvo, C., J.M. El agua pesada y su importancia en biologia. *Rev. de med. y aliment.* 2:10-14 1935.
- D78 Casazza, R. Alcune ricerche, in campo dermato-venereologico, con l'acqua "pesante" (ossido di deuterium) *Gior. Ital. di dermat. e. sif.* 79:759-63 1938.

- D79 Cavanagh, B., Raper, H.S. A study of the passage of fatty acids of food into lipins and glycerides of the body using deuterium as an indicator. *Biochem. Jour.* 33:17-21 1939.
- D80 Champetier, G. Deutérium et composés de deutérium. Tables annuelles de constantes. Nr. 1. Paris: Hermann and Cie. 80 pp. Fr. 40.
- D81 Champetier, G., Viallard, R. Penetration of water into the cellulose lattice. Interchange of H and D between cellulose and heavy water *Compt. rend.* 205:1387-8 1937.
- D82 Champetier, G., Viallard, R. Exchange reaction of cellulose and heavy water. Hydration of cellulose. *Bull. Soc. Chim.* 5:1042-8 1938.
- D83 Clark, H.T. The work of the Medalist. *Chem. Eng. News* 23:621-2 1945.
- D84 Clemo, G.R., Swan, G.A. Synthesis of heavy dl-adrenaline. *J. Chem. Soc.* 1942:395-7 1942.
- D85 Cohen, E.J. Nichols Medal awarded to du Vigneaud Vincent du Vigneaud - the Man *Chem. Eng. News* 23:620-1 1945.
- D86 Cohn, M., Simmonds, S., Chandler, J.P. du Vigneaud, V. The effect of the dietary level of methionine on the rate of transmethylation reactions in vivo. *J. Biol. Chem.* 162:343-51 1946.
- D87 Committee on Growth. Symposium on the Use of Isotopes in Biological Research March 3 and 4, 1947.
- D88 Cope, Oliver; Blatt, Hester; Ball, M.R. Gastric secretion III. The absorption of heavy water from pouches of the body and antrum of the stomach of the dog. *J. Clin. Invest.* 22:111-15
- D89 Craig, F.N., Trelease, S.F. Photosynthesis of *Chlorella* in heavy water. *Am. J. Bot.* 24:232-242 1937.



- D90 Curry, J., Pratt, R., Trelease, S.F. Does dilute heavy water influence biological processes? *Sci.* 81:275-77 1935.
- D91 Curry, James, and Trelease, Sam F. Influence of Deuterium Oxide on the rate of Photosynthesis. *Science* 82:18 1935.
- D92 Darmois, E. Industrial manufacture and applications of heavy water and of deuterium derivatives. *Mecanique, Suppl. Tech.ind.chim.* No.284 bis, pp 16-18 1939.
- D93 Davoud, J.G., Hinshelwood, C.N. Kinetics of the thermal decomposition of fully deuterated diethyl ether. *Proc. Roy. Soc. (London)* A174:50-6 1940.
- D94 Dole, M. The natural separation of the isotopes of hydrogen *J. Am. Chem. Soc.* 56:999 1934
- D95 Donatelli, Leonardo L'azione dell'acqua pesante (ossido di deuterio) su alcuni organi ed apparate della vita vegetative. (The action of heavy water (deuterium oxide) on some organs and the vegetative nervous system.) *Arch. Ital. Sci. Farmacol.* 7:201-228 1938.
- D96 Dujarric de la Riviere, R., Roux, E. L'eau lourde a-t-elle une action sur les bacterias? *Ann.Inst.Pasteur* 56:10-16 1936.
- D97 von Dungern, M. Hat schweres Wasser Einfluss auf physiologische Vorgänge? *Ztschr. f. Biol.* 97:187-94 1936.
- D98 von Dungern, M. Welchen Einfluss hat schweres Wasser auf Lebensvorgänge? *Med. Welt* 11:1054-5 1937.
- D99 Dybing, O., Guldberg, G., Hansen, K. Pathologisch-anatomische Veränderungen bei subakuter Deuteriumoxydvergiftung von Mäusen. *Klin. Wchnschr.* 17:1585 1938.

- D100 Ehrenwald, H., Kolisch, E. Über familiäre Tieflandstruma mit Untersuchungen über den Deuterium-oxydgehalt eines "Kropfbrunnens." Klin. Wchnschr. 16:462-4 1937.
- D101 Emeleus, H.J., James, F.W., King, A., Pearson, T.G., Purcell, R.H., Briscoe, H.V.A. The isotopic ratio in hydrogen: A general survey by precise density comparisons upon water from various sources. J. Chem. Soc. (London) August:1207-1219 1934.
- D102 Ehrlich, G., Waelsch, H. The position of the higher fatty aldehydes in fatty acid metabolism of rat muscle. J. Biol. Chem. 163:no.1 195-202 1946.
- D103 Erlenmeyer, H., Verzar, F. Hat schweres Wasser Einfluss auf Physiologische Vorgänge? Ztschr. F. Biol. 97:519-21 1936.
- D104 Ewart, A.J. The influence of heavy water on plants. Austral. J. Exp. Biol. and Med. Sci. 13:9-15 1935.
- D105 Fenger-Eriksen, K., Krogh, A., Ussing, H. Micro-method for accurate determination of  $D_2O$  in water. Biochem. J. 30:1264-9 1936.
- D106 Fischer, A. (Copenhagen) Wachstum von Gewebezellen in schwerem Wasser Protoplasma 26:51-5 1936.
- D107 Fishman, W.H., Cohn, M. A comparative study of acetylation in vivo of phenylaminobutyric acid with p-amino-benzoic acid and sulfanilamide J. Biol. Chem. 148:619-626 1943.
- D108 Flexner, L.B., Gellhorn, A., Merrell, M. Studies on rates of exchange of substances between the blood and extravascular fluid; I The exchange of water in the guinea pig. J. Biol. Chem. 144:35-40 1942.
- D109 Forjaz, A., de Pereira, Jacobsohn, K.P. Investigations on the mechanics of fermentation in presence of heavy water. Compt. rend. 17 me Congr. Chim ind. Paris, Sept-Oct. 1937; 487-93.



- D110 Forjaz, A.P., Jacobsohn, K.P. Mechanism of fermentation in presence of heavy water. Congr. Chim. Ind. Compt. rend. 18 me, Congr. Nancy Sept-Oct. 1938: 736-40 1938.
- D111 Forjaz, A.P., Jacobsohn, K.P., Tapadinhas, J. Enzyme equilibrium in the presence of heavy water; experiments with fumarases. Bull. Soc. Chim. Biol. 19:1194-9 1937.
- D112 Forjaz, A.P., Jacobsohn, K.P., Tapadinhas, J. Influence of deuterium oxide on enzymic action of aconitases. Bull. Soc. Port. Sci. Nat. 13: 37-41 1939.
- D113 Forjaz, A.P., Jacobsohn, K.P., Tapadinhas, J. Intervention of deuterium in enzymic processes. Bull Soc. Port. Sci. Nat. 13:71-3 1940.
- D114 Foster, G.L., Keston, A.S., Rittenberg, D., Schoenheimer, R. Deuterium as an indicator in the study of intermediary metabolism. XII. The action of proteolytic enzymes on peptides in heavy water. J. Biol. Chem. 124:159-61 1938.
- D115 Foster, G.L., Rittenberg, D., Schoenheimer, R. Deuterium as indicator in study of intermediary metabolism; XIV biological formation of deuterioamino acids. J. Biol. Chem. 125:13-22 1938.
- D116 Fox, D.L. Heavy water and metabolism. Quart. Rev. Biol. 9:342-6 1934.
- D117 Fox, D.L. Concerning enzymic reactions in heavy water. J. Cellular and Comp. Physiol. 6:405-24 1935.
- D118 Fox, D.L., Craig, R. Concerning enzymic reactions in heavy water. II. Deuterium and the hydrolysis of starch. Proc. Soc. Exp. Biol. and Med. 33:266-9 1935.
- D119 Fox, D.L., Cupp, E.E., McEwen, G.F. Low concentrations of deuterium oxide and the growth of marine diatoms. Proc. Soc. Exp. Biol. and Med. 34:575-81 1936.

- D120 Fresenius, R., Dick, W. Untersuchungen von Wiesbadener Hellquellen auf ihren Gehalt an schwerem Wasser. Balneologie 4:468-75 1937.
- D121 Fritsman, E.K. Heavy oxygen and superheavy water. Chem. Sentr. II:2633 1937.
- D122 G, Oswaldo Bueno Heavy water. Politecnica (Ecuador) 1:306-12 1936
- D123 Gaw, H.Z. IV. The effect of heavy water Arch. Protistenk. 87:213-24 1936.
- D124 Gellhorn, A., Flexner, L.B. Transfer of water across the placenta of the guinea pig. Am. J. Physiol. 136:750-56 1942.
- D125 Gilfillan, E.S. Jr. The isotopic composition of sea water. J. Am. Chem. Soc. 56:406 1934.
- D126 Govaerts, J., Lambrechts, A. Penetration of water into erythrocytes with heavy water as indicator. Nature 157:301 1946.
- D127 Gunther, V.G., Bonhoeffer, K.F. The fixation of heavy hydrogen in growing organisms Z. Physik, Chem. A180:185-210 1937.
- D128 Gunther, G., Bonhoeffer, K.F. Introduction of heavy hydrogen into growing organisms. VI. Biological fat synthesis. Z. Physik. Chem. A1183:1-8 1938.
- D129 Hackh, Ingo W.E. and Westling, E.H. A possible cause of old age. Science 79:231 1934.
- D130 Hahn, L. and Hevesy, G. Rate of penetration of ions through the capillary wall Acta Physiologica Scandinavica 1: 347 - 361 1941.
- D131 Hammett, F.S., Barbour, H.G. Retardation of growth of Obelia geniculata by deuterium oxide. Growth 3:403-8 1940.
- D132 Hansen, K. (Oslo) Einige orientierende Versuche uber die Wirkung von Deuteriumoxyd auf Mikroben Acta path. et. microbiol. Scandinav. supp. 26 pp 123-5 1936.



- D133 Hansen, K. (Oslo), Blegen, E. Versuche über die Wirkung schweren Wassers auf Mikroben Klin Wehnschr 14:1113 1935.
- D134 Hansen, K. (Oslo), Bruusgaard, A. To what extent can radioactive medicines cause resorptive intoxications? Nord. Med. (Norsk. Mag. f. laegevidensk.) 2:979-84 1939.
- D135 Hansen, K., Dybing, O. Quantitative Mikrobestimmung von Deuteroalkohol. Biochem. Zeitschr. 298:110-4 1938.
- D136 Hansen K., (Oslo), and Dybing, O. Die narkotische Starke des Deuteroalkohols im Vergleich mit Athylalkohol Arch.f.exper.Path.u. Pharmakol 191:275-80 1938.
- D137 Hansen, K., Dybing, O. Einige orientierende Versuche über die narkotische Starke von Deutero-Athylather ( $C_2D_5OC_2D_5$ ) im Vergleich mit Athylather. Arch. Exp. Path.u. Pharmakol. 192:600-2 1939.
- D138 Hansen, K. (Oslo), Rustung, E. Untersuchungen über die biologischen Wirkungen von "schwerem Wasser" bei warmblütigen Wieren. Klin. Wehnschr. 14:1521-5 1936.
- D139 Hansen, K. (Oslo), Wulfert, K. Untersuchungen über die Wirkung von Deuteriumoxyd auf das Wachstum junger Tiere Arch.f.exper.Path.u. Pharmakol. 190:671-80 1938.
- D140 Harvey, E. Newton Biological effects of heavy water. Biol. Bull. 66:91-96 1934.
- D141 Harvey, E.N. Taylor, G.W. The oxygen consumption of luminous bacteria in water containing deuterium oxide. J. Cell. and Comp. Physiol. 4:357 1934.
- D142 Herbst, R.M., Rittenberg, D. The transamination reaction. The mechanism of the reaction between alpha keto acids and alpha amino acids. J. Org. Chem. 8:380-9 1943.

- D 42 Herrmann, J.B. Pharmacological action of deuterium oxide; VIII Action on central nervous system. J. Pharmacol. and Exper. Ther. 67:265-75 1939.
- D144 Hermann, J.B., Barbour, H.G. Catatonia produced by introduction of heavy water into cerebrospinal fluid. Science 86:244-5 1937.
- D145 Hevesy, G. and Hofer, E. Diplogen and fish. Nature 133:495 1934.
- D146 Hevesy, G. , Hofer, E. Der Austausch des Wassers im Fischkorper. Hoppe Seyler's Zeitschr. Physiol. Chem. 225:28-34 1934.
- D147 Hevesy, G. , Hofer, E. Elimination of water from human body. Nature 134:879 1934.
- D148 Hevesy, G. Hofer, E. Die Verweilzeit des Wassers im menschlichen Korper, untersucht mit Hilfe von "schwerem" Wasser als Indicator. Klin. Wchnschr. 13:1524 1934.
- D149 Hevesy, G. , Hofer, E., Krogh, A. The permeability of the skin of frogs to water as determined by  $D_2O$  and  $H_2O$ . Skand. Arch. Physiol. 72:199-214 1935.
- D150 Hevesy, G., Jacobsen, C.F. Rate of passage of water through capillary and cell walls. Acta Physiol. Scand. 1:11-18 1941.
- D151 Hoberman, H.D., Rittenberg, D. Biological catalysis of the exchange reaction between water and hydrogen. J. Biol. Chem. 147, 211-27 1943.
- D152 Hughes, A.H., Yudkin, J., Kemp, I. Rideal, E.K. Some reactions with heavy water J. Chem. Soc. (London) July:1105-1112 1934.
- D153 Indovina, R., Citarda, A. The action of deuterium oxide on carbohydrate metabolism. Biochim. terap. sper. 24:236-47 1937.
- D154 Indovina, R., Citarda, A. The physical, chemical, and biological qualities of heavy water. Biochim. terap. sper. 24:285-98 1937.
- D155 Keston, A.S., Rittenberg, D. and Schoenheimer, R. Determination of Deuterium in organic compounds. J. of Biol. Chem. 122:227-37 1937.



- D156 Kinosita, R., Nakamura, H. Biological experiments with heavy water. Tr. Soc. Path. Jap. 25:403-6 1936.
- D157 Kinsey, V.E., Grant, M., Cogan, D.G. Water movement and the eye. Arch. Ophthalmol. 27:242-52 1942.
- D158 Kogle, F., Erxleben, H., VanVeersen, G.J. The chemistry of tumors. IX. Determination of d-glutamic acid in tumor hydrolyzates with D as indicator. Z. Physiol. Chem. 277:251-83 1943.
- D159 Koizumi, M., Titani, T. The exchange of hydrogen atoms between pyrrole and water. Preliminary communication. Bull. Chem. Soc. Japan 12:107-8 1937.
- D160 Koizumi, M., Titani, T. Exchange reaction of hydrogen atoms between sugar and water. Bull. Chem. Soc. Japan 13:427-36 1938.
- D161 Koizumi, M., Titani, T. Exchange of hydrogen atoms between pyrrole and its methyl derivatives and water. I. Exchange of hydrogen atoms between pyrrole and water. Bull. Chem. Soc. Japan 13:85-94 1938.
- D162 Konikova, A.S., Kritsman, M.G., Teis, R.V. Study of the mechanism of transamination by means of deuterium. XVII. Formation and decomposition of amino acids by intermolecular transfer of the amino group. Biokhimiya, 7, 86-92 1943.
- D163 Kredel, F.E., Harkins, H.N., Harkins, W.D., Toxicity of heavy water. Proc. Soc. Exper. Biol. and Med. 32:5-6 1934.
- D164 Kritsman, M.G., Konikova, A.S. Application of the heavy isotopes of hydrogen and nitrogen in biochemistry. Advances in Modern Biol. USSR 15, 27-47 1943.
- D165 Krogh, A. Use of deuterium in biological work. Enzymologia 5:185-9 1938.

- D166 Krogh, A., Ussing, H. Exchange of hydrogen between free water and organic substances in living organism. Skandinav. Arch.f.Physiol. 75:90-104 1936.
- D167 Krogh, A., Ussing, H.H. A note on the permeability of trout eggs to  $D_2O$  and  $H_2O$ . J. Exptl. Biol. 14:35-7 1937.
- D168 Krogh, A., Ussing, H.H. Deuterium built into proteins and their amino acids in vivo and in vitro. Compt. rend. trav. lab. Carlsberg, Ser. Chim. 22:282-7 1938.
- D169 Lewis, G.N., The biochemistry of water containing hydrogen isotope. J. Am. Chem. Soc. 55:3503-4 1933.
- D170 Lewis, G.N., The biology of heavy water Science 79:151 1934.
- D171 Linderstrom-lang, K., Jacobsen, O., Johansen, G. Measurement of the deuterium contained in mixtures of  $H_2O$  and  $D_2O$ . Compt. rend. trav. lab. Carlsberg. 25:17 1938.
- D172 Lockemann, G. Über desinfektionsversuche mit "schwerem wasser." Wissensch. Woche zu Frankfurt A.M. 3:170 1935.
- D173 Lucke, B., Harvey, E.N. The permeability of living cells to heavy water (deuterium oxide) J. Cell. and Comp. Physiol. 5:473-82 1935.
- D174 Macht, D.I., Bryan, H.F. Effect of deuterium oxide on action of some enzymes. Proc. Soc. Exp. Biol. and Med. 34:190-93 1936.
- D175 Macht, D.I. and Davis, M.E. Some pharmacological experiments with deuterium J. Am. Chem. Soc. 56:246 1934.
- D176 Mark, H., Wald, M. Über den gegenwertigen stand unserer Kenntnisse vom schweren Wasserstoff und dem schweren Wasser. Protoplasma 23:109-127 1935.
- D177 McDougall, E.J., Verzar, F., Erlenmeyer, H., Gaertner, H. Heavy water in animal body. Nature, London 134:1006 1934.



- D178 Melka, J. Physiologic and biochemical aspects of heavy water.  
Bratisl. lekar, listy 15:50-62 1935.
- D179 Melot, Georgette J. Effects of deuterium oxide on respiration of germinating seeds. Proc. Soc. Exp. Biol. and Med. 32:79-83 1934.
- D180 Merrell, M., Gellhorn, A. and Flexner, L.B. Studies on rates of exchange of substances between the blood and extravascular fluid II. The exchange of sodium in the guinea pig J. of Biol. Chem. 153:83-89 1944.
- D181 Meyer, Herbert Breeding of algae in highly concentrated heavy water. Naturwissenschaften 24:346 1936.
- D182 Meyer, S.L. Alleged stimulation of moulds by paraffin in heavy water. Nature (London) 134:665 1934.
- D183 Meyer, S.L. Deuterium oxide and Aspergillus. Science 79:210 1934.
- D184 Meyer, S.L. Deuterium oxide and living organisms. J. Tenn. Acad. Sci. 9:225-231 1934.
- D185 Meyer, S.L. Further contributions in the study of the biological effects of heavy water. J. Tenn. Acad. Sci. 11:269-277 1936.
- D186 Meyer, S.L. Further observations on deuterium oxide and Aspergillus J. of the Tenn. Acad. of Sci. IX:295-7 1934.
- D187 Meyer, S.L. Recent advances in the study of the biological effects of heavy water. J. of the Tenn. Acad. of Sci. X:111-5 1935.
- D188 Miller, J.R., Wagner, A. The distribution and rate of formation of synthesized cholesterol. J. Clin. Invest. 20:466 1941.
- D189 Mills, G. Alexander Dissociation of carbonic acid in ordinary and in heavy water. J. Am. Chem. Soc. 62:449 1940.
- D190 Moore, F.D. Determination of total body water and solids with isotopes. Science 104:157 Aug. 1946.

- D191 Morehouse, M.D. Metabolism of two di-deuterobutyric acids as indicated by deuterium content of excreted beta-hydroxy-butyric acid. Proc. Soc. Exper. Biol. and Med. 41:595-6 1939.
- D192 Morehouse, M.G., Studies on ketosis: XVI. The metabolism of  $\alpha$ ,  $\beta$ - and  $\beta$ ,  $\gamma$ -deuterobutyric acids in the fasting rat. J. Biol. Chem. 129:769-79 1939.
- D193 Morehouse, M.G. Studies on ketosis XXIII. The metabolism of isotopic tributyrin and partially hydrogenated linseed oil. J. of Biol. Chem. 155:33-8 1944.
- D194 Morehouse, M.G., Deuel, H.J.Jr. Metabolism of  $\alpha$ ,  $\beta$  and  $\beta$ ,  $\gamma$ -deuterocaproic acids. Proc. Soc. Exper. Biol. and Med. 45, 96-8 1940.
- D195 Munzberg, F.K., Haurowitz, F. Action of heavy water on proteins and amino acids at body temperature. Z. Physiol. Chem. 256:271-2 1938.
- D196 Nakao, T., Imase, H., Ihashi, S. Über die pharmakologischen wirkungen von deuteriumoxide. Sei-I-Kai M.J. (Abstr.Sect) 56:2-3 1937.
- D197 Orban, G. Concentration of heavy water in human organism. Orvosi hetil. 79:193. 1935.
- D198 Pacsu, E. The alcoholic fermentation of d-glucose in deuterium water. J. Am. Chem. Soc., 56:245 1934.
- D199 Pacsu, E. The mutarotation of  $\alpha$ -d-glucose in deuterium water. J. Am. Chem. Soc. 56:745 1934.
- D200 Parpart, A.K. Permeability of mammalian erythrocyte to deuterium oxide (heavy water). J. Cell. and Comp. Physiol. 7:153:62 1936.
- D201. Peters, H.C. Application of general fluidcircuit theory to (absorption from intestine of) chloride, bromide and deuterium oxide. Bull. Math. Biophys. 3:149-52 1943.



- D202 Plantefol, L., Champetier, G. Action de L'eau dense (oxyde de deutohydrogene) sur la germination d'un pollen. Compt. Rend. Acad. Sci. (Paris) 200:423-425 1935.
- D203 Plantefol, L., Champetier, G. Action de l'eau dense (oxyde de deutohydrogene) sur les animaux reviviscents. Compt. Rend. Acad. Sci. (Paris) 200:587-589 1935.
- D204 Pratt, Robertson Deuterium and living organisms. Torrey 36:133-8 1936.
- D205 Pratt, Robertson Growth of Erysiphe Germ Tubes in Deuterium Oxide after Exposure to Water. Am. J. Botany 24:2 76-82, Feb. 1937.
- D206 Pratt, Robertson Growth of germ tubes of erysiphe spores in deuterium oxide. Am. J. Bot. 23:422-431 1936.
- D207 Pratt, Robertson Influence of Deuterium Oxide on the Growth of Chlorella Vulgaris Am. J. Bot. 25:9 699-701 Nov. 1938.
- D208 Pratt, R., Craig, F.N., Trelease, S.F. Influence of D<sub>2</sub>O on photochemical and dark reactions of photosynthesis. Science 85:271-3 1937.
- D209 Pratt, R., Curry, J. Growth of roots in deuterium oxide. Am. J. Bot. 24:412-416 1937.
- D210 Pratt, R. and Trelease, S.F. Influence of deuterium oxide on photosynthesis in flashing and in continuous light. Am. J. of Bot. 25:133-39 1938.
- D211 Racine, M. L'eau lourde et la medecine Gaz. Med. de France pp 232-33 March 1, 1935.
- D212 Ratner, S. Conversion of d-glutamic acid to pyrrolidonecarboxylic acid by the rat. J. Biol. Chem. 152:559-64 1944.
- D213 Ratner, S. Schoenheimer, R., Rittenberg, D. Studies in protein metabolism. XIII. The metabolism and inversion of d(4-)-leucine studied with two isotopes. J. of Biol. Chem. 134:653 1940.

- D214 Ratner, S., Weissman, N. Schoenheimer, R. The metabolism of d-lysine investigated with deuterium and heavy nitrogen. J. Biol. Chem. 147:549-56 1943.
- D215 Rea, C.E., Yuster, S. Effect of deuterium oxide on rat sarcoma. R-39. Proc. Soc. Exper. Biol. and Med. 31:1058-60 1934.
- D216 Richards, Oscar W. The effect of deuterium on the growth of yeast. J. Bact. 28:289-294 1934.
- D217 Richards, O.W. The growth of yeast in water containing deuterium. Am. J. Bot. 20:679 1933.
- D218 Rittenberg, D., Keston, A.S., Schoenheimer, R., Foster, G.L. Deuterium as indicator in the study of intermediary metabolism; XIII. Stability of hydrogen in amino acids. J. Biol. Chem. 125:1-12 1938.
- D219 Rittenberg, D., Schoenheimer, R. Deuterium as indicator in study of intermediary metabolism. XI. Further studies on biological uptake of deuterium into organic substances, with special reference to fat and cholesterol formation. J. Biol. Chem. 121:235-53 1937.
- D220 Rittenberg, D., Schoenheimer, R. Deuterium as indicator in study of intermediary metabolism. VIII. Hydrogenation of fatty acids in animal organism. J. Biol. Chem. 117:485-90 1937.
- D221 Rittenberg, D., Schoenheimer, R. Deuterium as indicator in study of intermediary metabolism. Methods - J. Biol. Chem. 111:169 1935.
- D222 Rittenberg, D., Schoenheimer, H., Evans, E.A., Jr. Deuterium as indicator in study of intermediary metabolism. X. Metabolism of butyric and caproic acids. J. Biol. Chem. 120:503-510 1937.
- D223 Robinson, R.A. Relative osmotic co-efficients of sodium and potassium chloride in deuterium oxide at 25°. Trans. Faraday Soc. 35:1220-1222 1939.



- D224 Roloff, M., Ratner, S., Schoenheimer, R. The biological conversion of ornithine into proline and glutamic acid. J. Biol. Chem. 136: 561 - 1940.
- D225 Ronaess, Egil Conductivity of potassium chloride in heavy water. Kgl. Norske Videnskab. Selskabs, forh. 12:133-136 1940.
- D226 Salcedo, Juan, Jr., Stetten, Dewitt, Jr. The turnover of fatty acids in the congenitally obese mouse. J. Biol. Chem. 151, 413-16 1943.
- D227 Schenck, J.R., Simmonds, S., Cohn, M., Stevens, C.M., Vigneaud, V. du. The relation of transmethylation to anserine. J. Biol. Chem. 149:355-59 1943.
- D228 Schmidt-Nielsen, S., Schmidt-Nielsen, K. The behavior of Drosophila on nutrient media containing deuterium oxide. Kgl. Norske Videnskab. Selskab, Forh. 9:28-30 1936.
- D229 Schoenheimer, R. Investigation of intermediary metabolism with aid of heavy hydrogen; Harvey lecture. Bull. N.Y. Acad. Med. 13:272-95 1937.
- D230 Schoenheimer, R. The use of organic compounds containing stable isotopes for the study of intermediary metabolism. J. App. Physics 12:322 1941.
- D231 Schoenheimer, R., Ratner, S. The metabolism of proteins and amino acids Ann. Rev. Biochem. 10:197-220 1941.
- D232 Schoenheimer, R., Ratner, S., Rittenberg, D. Studies in protein metabolism. X. The metabolic activity of body proteins investigated with 1 (-) - leucine containing two isotopes. J. Biol. Chem. 130:703 1939.
- D233 Schoenheimer, R., Ratner, S., and Rittenberg, D. The process of continuous deamination and reamination of amino acids in the proteins of normal animals. Science 89:272-3 1939.

- D234 Schoenheimer, R., Rittenberg, D. Deuterium as indicator in study of intermediary metabolism; IX Conversion of stearic acid into palmitic acid in organism. J. Biol. Chem. 120:155-65 1937.
- D235 Schoenheimer, R., Rittenberg, D. Deuterium as indicator in the study of intermediary metabolism. J. Biol. Chem. 111: 163 1935.
- D236 Schoenheimer, R., Rittenberg, D. Deuterium as indicator in study of intermediary metabolism; desaturation of fatty acids in organism. J. Biol. Chem. 113:505-10 1936.
- D237 Schoenheimer, R., Rittenberg, D. Deuterium as indicator in study of intermediary metabolism; III. Role of fat tissues. J. Biol. Chem. 111: 175-181 1935.
- D238 Schoenheimer, R., Rittenberg, D., Deuterium as indicator in study of intermediary metabolism; Synthesis and destruction of fatty acids in organism. J. Biol. Chem. 114:381-96.
- D239 Schoenheimer, R., Rittenberg, D., Berg, B.N., Rousselot, L. Deuterium as an indicator in the study of intermediary metabolism. VII. Studies in bile acid formation. J. Biol. Chem. 115:635-40 1936.
- D240 Schoenheimer, R., Rittenberg, D., Graff, M. Deuterium as indicator in study of intermediary metabolism. IV. Mechanism of coprosterol formation. J. Biol. Chem. 111:183 1935.
- D241 Schon, M. Die biologischen Wirkungen des schweren Wassers. Munchen, Med. Wehnschr. 81:1277 1934.
- D242 Shoup, C.S., Meyer, S.L. The action of deuterium oxide in low concentration on the course of gas-production by brewer's yeast. J. Tenn. Acad. Sci. 10:127-130 1935.
- D243 Selwood, P.W. Heavy water. J. Chem. Education 18: 515-520 1941.



- D244 Shapiro, A., Koster, H., Rittenberg, D., Schoenheimer, R. The origin of fecal fat in the absence of bile, studied with deuterium as an indicator. *Amer. Jour. Physiol.* 117:525-528.
- D245 Shibata, K., Watanabe, A. Zellatmung und Kohlensaure-Assimilation in Schwerem Wasser. *Acta Phytochimica (Tokyo)* 9:107-114 1936.
- D246 Silvertri, S. Il deuterio in biologia *Fisiol.e med.* 10:291-297 1939.
- D247 Simmonds, S., Cohn, M., Chandler, J.P., Vigneaud, V. du The utilization of the methyl groups of choline in the biological synthesis of methionine. *J. Biol. Chem.*, 149:519-25 1943.
- D248 Simmonds, S., DuVigneaud, V. A further study of the lability of the methyl group of creatine. *Proc. Soc. Exper. Biol. Med.* 59:293-4 1945.
- D249 Simmonds, S., Vigneaud, V. du Transmethylation as a metabolic process in man. *J. Biol. Chem.* 146:685-86 1942.
- D250 Smith, P.K., Trace, J., Barbour, H.G. Fate of deuterium in mammalian body. *J. Biol. Chem.* 116:371-6 1936.
- D251 Sperry, W.M., Waelsch, H., Stoyanoff, V.A. Lipide metabolism in brain during myelination. *J. Biol. Chem.* 135:297-302 1940.
- D252 Sperry, W.M., Waelsch, H. Lipid metabolism in brain and other tissues of the adult rat. *J. of Biol. Chem.* 133:281 1940.
- D253 Sperry, W.M., Waelsch, H., Stoyanoff, V.A. Lipid metabolism in brain and other tissues of the rat. *J. Biol. Chem.* 135:281-90 1940.
- D254 Steacie, E.W.R. Die enzymatische Rohrzuckerinversion in schwerem Wasser. *Zeitschr. Physik. Chem. B.* 27:6-10 1934.
- D255 Steacie, E.W.R. Die enzymatische Spaltung von Salicin durch Emulsin in Schwerem Wasser. *Zeitschr. Physik. Chem. Abt. B* 28:236-38 1934.
- D256 Steinert, B. "Heavy" water: A review of the literature related to brewing. *Communications Sci. and Practice Brewing, Wallerstein Lab.* 5:21-24 1939.

- D257 Stekol, A.J., Hamill, W.H. On the nonlabile deuterium of amino acids subjected to treatment in the medium of dilute deuterium oxide. J. Biol. Chem. 120:531-6 1937.
- D258 Stekol, J.A., Hamill, W.H. Synthesis of protein and amino acids in mice with the aid of deuterium. Proc. Soc. Exper. Biol. and Med. 35:591-3 1937.
- D259 Stephens, G.A. Therapeutic value of "heavy water." Prescriber 33:43-44 1939.
- D260 Stern, K., Dancey, T.E. Injection of heavy water into cerebrospinal fluid space. Proc. Soc. Exper. Biol. and Med., 48:619-20 1941.
- D261 Stetten, DeWitt, Jr. Metabolism of a paraffin. J. Biol. Chem. 147:327-332 1943.
- D262 Stetten, DeWitt, Jr. Studies in carbohydrate metabolism. IV. The turnover of glycogen in the liver and carcass of rats fed galactose. J. Biol. Chem. 159:123-127.
- D263 Stetten, DeWitt, Jr., Boxer, Geo. E. Studies in carbohydrate metabolism. I. The rate of turnover of liver and carcass glycogen, studied with the aid of Deuterium. J. Biol. Chem. 155:231-6 1944.
- D264 Stetten, D., Jr., Grail, G.F. The rates of replacement of depot and liver fatty acids in mice. J. Biol. Chem. 148:509-15 1943.
- D265 Stetten, D., Jr. Klein, B.V. Studies in carbohydrate metabolism. V. Effects of adrenalin and insulin upon glycogenesis in rats. J. Biol. Chem. 159:593-602 1945.
- D266 Stetten, DeWitt, and Klein, B.V. Studies in Carbohydrate Metabolism VI. Effects of Hypo and Hyperinsulinism in Rabbits. J. of Biol. Chem. 162:377-82 1946.
- D267 Stetten, DeW Jr., Klein, B.V. Studies in carbohydrate metabolism. VIII The origin of the stable hydrogen in glycogen formed from various precursors. J. of Biol. Chem. Vol. 165:157-62 Sept. 1946.



- D268 Stetten, DeW. Jr. and Klein, B.V. Effect of insulin level upon lipogenesis. Federation Proc. Vol 5, No.1, (no pp) March 1946.
- D269 Stetten, D., Jr., Salcedo, J., Jr. The source of the extra liver fat in various types of fatty liver. J. Biol. Chem. 156:27-32 1944.
- D270 Stetten, DeW., Jr., Schoenheimer, R. The biological relations of the higher aliphatic alcohols to fatty acids. J. Biol. Chem. 133:347-57 1940.
- D271 Stetten, DeW., Jr., Schoenheimer, R. The conversion of palmitic acid into Stearic and Palmitoleic Acids in rats. J. Biol. Chem. 133:329-345 1940.
- D272 Stetten, DeW. Jr., and Stetten, M.R. Studies in carbohydrate metabolism VII. The distribution of deuterium in a sample of deuterio glucose excreted by a diabetic rabbit. J. of Biol. Chem. 165:147-55 Sept. 1946.
- D273 Stetten, M.R., Schoenheimer, R. The metabolism of l(-)-proline studied with the aid of deuterium and isotopic nitrogen. J. Biol. Chem. 153:113-32 1944.
- D274 Stetten, M.R. and DeWitt Stetten, Jr. Biological conversion of inositol into glucose. J. of Biol. Chem. 164:85-91 July, 1946.
- D275 Stewart, W.W. The biological separation of heavy water. J. Amer. Chem. Soc. 56:1422-1423 1934.
- D276 Stewart, W.W., Holcomb, R. The biological separation of heavy water. J. Am. Chem. Soc. 56:1422 1934.
- D277 Stockl, K. Der schwere Wasserstoff--Das schwere Wasser. Med. Klin. 32:1105-9 1936.
- D278 Sugiura, K., Chesley, L.C. Effect of heavy water (deuterium Oxide) on viability of mouse sarcoma and rat carcinoma Proc. Soc. Exper. Biol. and Med. 31:1108 1934.

- D279 Sugiura, K., Chesley, L.C. Effect of heavy water (duterium oxide) on viability of mouse sarcoma and melanoma. Proc. Soc. Exp. Biol. and Med. 31:659-661 1934.
- D280 Takeuti, T., Sibuya, T. Affinity of heavy water for living tissue. Bull. Tokyo Univ. Eng. 9:264-9 1940.
- D281 Taylor, G.W. Harvey, E.N. Respiration of yeast in water containing deuterium oxide. Prox. Soc. Exper. Biol. and Med. 31:954-7 1934.
- D282 Taylor, H.S. Research on heavy hydrogen at Princeton, Science 79:303 1934.
- D283 Terao, A., Inoue, Y. Effect of the heavy water on the population growth of the water-flea, *Moina macrocopa* Strauss. Proc. Imp. Acad. (Tokyo) 10:513-514 1934.
- D284 Theis, K. Heavy hydrogen in biological cellular processes. Wochschr. Brau. 55:36-9 1938.
- D285 Thompson, Jr., A.F., Cromwell, N.H. The preparation and properties of aldehydes containing deuterium in the functional group. J. Am. Chem. Soc. 61:1374 1941.
- D286 Thunberg, T. Influence of heavy water on some enzymic dehydrogenation processes. Enzymologia 3:56-61 1937.
- D287 Titani, Tosizo Application of heavy hydrogen and heavy oxygen in chemical investigations. (Japan) Chem. Rev. 6:12-26 1940.
- D288 Ueno, S., Ueno, Y. Hydrogenation of unsaturated acids with deuterium. J. Chem. Soc. Japan 57:794-7 1936.
- D289 Urey, H.C. Deuterium and its compounds in relation to biology. Cold Spring Harbor Symp Quant. Biol. 2:47-56 1934.
- D290 Urey, Harold C. Separation and use of stable isotopes J. App. Physics. 12:270 1941.



- D291 Urey, H., Failla, G. Concerning taste of heavy water Sci. 81:273 1936.
- D292 Ussing, Hans. H. The influence of heavy water on the development of amphibian eggs. Skand. Arch. Physiol. 72:192-198 1936.
- D293 Ussing, H.H. Glycogen formation in the liver studied by means of heavy hydrogen. Skand. Arch. Physiol. 77:85-6 1937.
- D294 Ussing, H.H. Exchange of H and D atoms between water and protein in vivo and in vitro. Skandinav. Arch.f.Physiol. 77:107-22 1937.
- D295 Ussing, H.H. Exchange of H and D atoms between water and protein in vivo and in vitro. Skandinav. Arch.f.Physiol. 78:225-41 1938.
- D296 Ussing, H.H. Use of amino acids containing deuterium to follow protein production in the organism. Nature 142:399-400. 1938.
- D297 Ussing, H.H. The fate or metabolism of deuterium introduced in some amino acids by heating with D<sub>2</sub>O and sulfuric acid. Acta Physiol. Scand. 2:222-6 1941.
- D298 Ussing, H.H. The rate of protein renewal in mice and rats studied by means of heavy hydrogen. Acta Physiol. Scand. 2:209-21 1941.
- D299 Van Heyningen, W.E. Stable isotopes as indicators in biology. Biol. Rev. Cambridge Phil. Soc. 14:420-450 1939.
- D300 Verzar, F., Haffter, C. Die Wirkung von "schwerem Wasser" (Deuterium Oxyd) auf isolierte Organe. Arch.f.d.ges. Physiol. 236:714-6 1936.
- D301 Vigneaud, V. du, Chandler, J.P., Cohn, M., Brown, G.B. The transfer of the methyl group from methionine to choline and creatine. J. Biol. Chem. 134:787-8 1940.
- D302 Vigneaud, V. du, Chandler, J.P., Moyer, A.W. The inability of creatine and creatinine to enter into transmethylation in vivo. J. Biol. Chem. 139:917-23 1941.

- D303 Vigneaud du, Chandler, Moyer, Keppel, The effect of choline on the ability of homocystine to replace methionine in the diet. J. Biol. Chem. 131:57 1939.
- D304 Vigneaud, V. du, Chandler, J.P. Simmonds, S., Cohn, M. The role of dimethyl- and monomethylaminoethanol in transmethylation reactions in vivo. J. Biol. Chem. 164:603-13 August 1946.
- D305 Vigneaud, du, Cohn, M., Chandler, J.P., Schenck, J.R., Simmonds, S. The utilization of the methyl group of methionine in the biological synthesis of choline and creatinine. J. Biol. Chem. 140:625-41 1941.
- D306 Vigneaud, V., Simmonds, S., Chandler, J.P., Cohn, M. Synthesis of labile methyl groups in the white rat. J. Biol. Chem. 159:755-756 1945.
- D307 Vigneaud, V. du, Simmonds, S., Cohn, M. A further investigation of the ability of sarcosine to serve as a labile methyl donor. J. Biol. Chem. 166:47-52 1946.
- D308 Visscher, M.B., Fetcher, E.S. Jr, Carr, C.W., Gregor, N.P., Bushey, M.S. Barker, D.E. Isotopic tracer studies on the movement of water and ions between intestinal lumen and blood. Am. J. Physiol. 142:550-75 1944.
- D309 Waelsch, H., Sperry, W.M. The composition of unsaponifiable lipids. J. Biol. Chem. 132:787-8 1940.
- D310 Waelsch, H., Sperry, W.M. Lipid metabolism of brain during early life. Proc. of Am. Soc. of Biol. Chem. April 15-19, 1941.
- D311 Waelsch, H., Sperry, W.M., Stoyanoff, V.A. A study of the synthesis and deposition of lipids in brain and other tissues with deuterium as an indicator. J. Biol. Chem. 135: 291-6 1940.
- D312 Waelsch, H. Sperry, W.M. Lipid metabolism in brain during myelination. J. Biol. Chem. 133: 1940.



- D313 Waelsch, H., Sperry, W.M., Stoyanoff, V.A. Lipid metabolism in brain during myelination. J. Biol. Chem. 135:297-302 1940.
- D314 Waelsch, H., Sperry, W.M., Stoyanoff, V.A. The influence of growth and myelination on the deposition and metabolism of lipids in the brain. J. Biol. Chem. 140:885-97 1941.
- D315 Washburn, E.W., Smith, E.R. The isotopic fractionation of water by physiological processes. Science 79:188 1934.
- D316 Weiser, H.H. Influence of deuterium oxide on growth and morphology of lactobacilli. Proc. Soc. Exper. Biol. and Med. 36:151-152 1937.
- D317 Weissman, N., Schoenheimer, R. XV Studies in protein metabolism, The relative stability of 1(+)-lysine in rats studied with deuterium and heavy nitrogen. J. Biol. Chem. 140:779 1941.
- D318 Widiger, A.H., Brown, W.G. Fractionation of the hydrogen isotopes in the distillation of ethyl alcohol. J. Am. Chem. Soc. 61:2453-4 1939.
- D319 Woglom, W.H., Weber, L.A. "Heavy water" and tumor growth. J.A.M.A. 102:1289-90 1934.
- D320 Wood, J.L., Vigneaud, V. du A new synthesis of cystine. J. Biol. Chem. 131:267. 1939.
- D321 Woodard, H.Q., Chesley, L.C. The growth of animals and plants in heavy water. Science 79:2060 1934.
- D322 Yamashita, H. Biological effects of deutron-deutron-neutrons. Nature, London 141:416-417 1938.
- D323 Zamenhof, S., Demerec, M. Heavy water and mutation. Genetics 28:96 1943.
- D324 Zamenhof, S., Demerec, M. Studies on induction of mutations by chemicals I. Experiments with heavy water. (Deuterium Oxide) Am. Naturalist. LXXVII:380-4 1943.
- D325 Zirpolo, G. Heavy water in biology. Riv. fis.mat.sci.nat.11:372-377 1937.

- D 326 Zirpolo, G. The effect of heavy water on organisms. Riv. fis. Mat. Sci. Nat. 13:367-370 1939.
- D 327 Zirpolo, G. The effect of heavy water on organisms. I. Boll. Soc. Nat. Napoli 49:137-146 1938.
- D 328 Zirpolo, G. The effect of heavy water on organisms. V. Experiments with the polychete annelid Nereis dumerilli. Boll. Soc. Naturalisti Napoli 50:33-39 1940.
- D 329 Zirpolo, G. Effect of heavy water on organisms. VIII. Studies with the gastropod mollusks Bittium scabrum Olivi and Phyllirhoe bucephala Peron and Lesseur and with the pteropod mollusks Creseis acicula Rang and Cleodora pyramidata L. Boll. Soc. Naturalista Napoli 51:3-15 1943.

Addendum .

- D 330 Schoenheimer, R. The dynamic state of body constituents. 81 pp. 1942.



ELEMENT 61

- 61 1 Hamilton, J. G. The metabolism of the fission products  
and the heaviest elements. Radiology 49: 325-43, 1947.

## FLUORINE

- Fl 1      Wills, J.H.      Secretion of intravenously injected fluorine in the submaxillary saliva of cats.      J. Dental Research      19:585-590, 1940.
- Fl 2      Volker, J.F., Hodge, H.C., Wilson, H.J., VanVoorhis, S.N.      The absorption of fluorides by enamel, dentin, bone, and hydroxyapatite as shown by the radioactive isotope.      J. Biol. Chem.      134:543-48, 1940.
- Fl 3      Volker, J.F., Sognnaes, R.F., Bibby, B.G.      Studies on the distribution of radioactive fluoride in the bones and teeth of experimental animals.      Am. J. Physiol.      132:707-12, 1941.



## GOLD

- Au 1      Ely, J.O.      The distribution of radiophosphorus and radio gold in rats after oral, intraperitoneal and subcutaneous administration. J. Franklin Inst.    230:125-30, 1940.

## HYDROGEN

See under: Deuterium; Tritium.



## IODINE

- I 1 Ariel, I., Bale, W. F., Downing, V., Hodges, H. C., Mann, W., Van Vorhis, S., Warren, S. L., Wilson, H. J. The distribution of radioactive isotopes of iodine in normal rabbits. *Am. J. Physiol.* 132:346-350 1941.
- I 2 Belanger, L. F., Leblond, C. P. A method for locating radioactive elements in tissues by covering histologic tissues with a photographic emulsion. *Endocrinol.* 39:8-13 1946.
- I 3 Baumann, E. J., Metzger, N., Marine, D. Mode of action of thiourea on the thyroid gland of rabbits. *Endocrinol.* 34:44-49 1944.
- I 4 Bloch, H. S., Ray, F. E. Organic radioiodo compounds for cancer research. *J. Natl. Cancer Inst.* 7:61 1946.
- I 5 Chagas, C., DeRobertis, E., Couceiro, A. Penetration of radioactive iodine in the thyroid gland colloid. *Texas Repts. Biol. Med.* 3: 170-178 1946.
- I 6 Chaikoff, I. L., Taurog, A., Reinhardt, M. O. The metabolic significance of protein-bound iodine of plasma: Study of its concentration under various conditions and of its rate of formation as measured with radioactive iodine. *Endocrinol.* 40:47-54 1947.
- I 7 Chapman, E. M., Evans, R. The treatment of hyperthyroidism with radioactive iodine. *Am. Med. Assoc.* 131:86-91 1946.
- I 8 Eisenman, A. J., Smith, P. K., Winkler, A. W., Elkinton, J. R. The transfer of ions across the stomach wall, studied by means of radioactive isotopes. *J. Biol. Chem.* (Proc. Am. Soc. Biol. Chem., 35th Ann. Mtg.) 140:XXXV 1941.

- I 9 Evans, R. D. "Isotopes; radioactive, measurement," in Medical Physics Chicago, 1944.
- I 10 Evans, T. C. Radioautographs in which tissue is mounted directly on a photographic plate. Proc. Soc. Exper. Biol. and Med. 64:315-315 1947.
- I 11 Franklin, A. L., Chaikoff, I. L. The effect of sulfonamides on the conversion in vitro of inorganic iodide to thyroxine and diiodotyrosine by thyroid tissue with radioactive iodine as indicator. J. Biol. Chem. 152:295-301 1944.
- I 12 Franklin, A. L., Chaikoff, I. L. The effect of sulfanilamide on the conversion in vitro of inorganic iodine to thyroxine and diiodotyrosine by thyroid slices. J. Biol. Chem. 143:719 1943.
- I 13 Franklin, A. L., Chaikoff, I. L., Lerner, S. R. The influence of goitrogenic substances on the conversion in vitro of inorganic iodide to thyroxine and diiodotyrosine by thyroid tissue radioactive I as indicator. J. Biol. Chem. 153:151-162 1944.
- I 15 Frantz, V. K., Ball, R. P., Keston, A. S., Palmer, W. W. Thyroid carcinoma and metastases: studied with radioactive iodine. Ann. Surg. 119:668-689 1944.
- I 16 Gibson, J. G., Seligman, A. M., Peacock, W. C., Fine, J., Aub, J. C., Evans, R. D. The circulating red cell and plasma volume and the distribution of blood in large and minute vessels in experimental shock in dogs measured by radioactive isotopes of iron and iodine. J. Clin. Invest. 26:126-144 1947.
- I 17 Gibson, J. G., Seligman, A. M., Peacock, W. D., Aub, J. C., Evans, R. D., Fine, J. The distribution of red cells and plasma in large and minute vessels of the normal dog, determined by radioactive isotopes of iron and iodine. J. Clin. Invest. 25:848-857 1946.



- I 18 Gorbman, A., Greaser, C. W. Accumulation of radioactive iodine by the endostyle of larval lampreys and the problem of homology of the thyroid. *J. Exper. Zool.* 89:391-405 1942.
- I 19 Gorbman, A., Evans, H. M. Correlation of histological differentiation with beginning of function of developing thyroid gland of frog. *Proc. Soc. Exp. Biol. and Med.* 47:103-106 1941.
- I 20 Gorbman, A., Evans, H. M. Beginning of function in the thyroid of the fetal rat. *Endocrinol.* 32:113-115 1943.
- I 21 Greenberg, D. M., Aird, R. B., Boelter, M. D. D., Campbell, W. W. Cohn, W. E., Murayama, M. M. A study with radioactive isotopes of the permeability of blood-cerebrospinal fluid barrier to ions. *Am. J. Physiol.* 140:47-64 1944.
- I 22 Gross, J., Leblond, C. P. The histological localization of radioactive elements; a review. *McGill Med. J.* 15:399-438 1946.
- I 23 Hamilton, J. G. Rates of absorption of radioactive isotopes of sodium, potassium, chlorine, bromine and iodine in normal human subjects. *Am. J. Physiol.* 124:667-668 1938.
- I 24 Hamilton, J. G. The use of radioactive tracers in biology and medicine. *Radiol.* 39:541-572 1942.
- I 25 Hamilton, J. G., Lawrence, J. H. Recent clinical developments in the therapeutic application of radiophosphorus and radioiodine. *J. Clin. Invest.* 21:624 1942.
- I 26 Hamilton, J. G., Soley, M. H. A comparison of the metabolism of iodine and of element 85 (eka-iodine). *Proc. Nat. Acad. Sci.* 26:483-489 1940.
- I 27 Hamilton, J. G., Soley, M. H. Studies in iodine metabolism of thyroid gland in situ by use of radio-iodine in normal subjects and in patients with various types of goiter. *Am. J. Physiol.* 131:135-143 1940.

- I 28 Hamilton, J. G., Soley, M. H. Studies in iodine metabolism by use of new radioactive isotope of iodine. Am. J. Physiol. 127:557-572 1939.
- I 29 Hamilton, J. G., Soley, M. H. Studies in physiology of normal and diseased thyroids of human beings by the use of radioactive iodine. J. Appl. Phys. 12:314 1941.
- I 30 Hamilton, J. G., Soley, M. H., Eichhorn, K. B. Deposition of radioactive iodine in human thyroid tissue. Univ. Calif. Publ. Pharmacol. 1:339-367 1941.
- I 31 Hamilton, J. G., Soley, M. H., Reilly, W. A., Eichhorn, K. B. Radioactive iodine studies in childhood hyperthyroidism. Am. J. Dis. Child. 66:495-502 1943.
- I 32 Hertz, S. Radioactive iodine as an indicator in thyroid physiology. III. Observations on rabbits and on goitre patients. Am. J. Roentgenol. 46:467 1941.
- I 33 Hertz, S., Roberts, A. Radioactive iodine as indicator in thyroid physiology. III. Iodine collection as criterion of thyroid function in rabbits injected with thyrotropic hormone. Endocrinol. 29:82-88 1941.
- I 34 Hertz, S., Roberts, A. Collection of iodine in the thyroid as a differential criterion in the diagnosis of two types of Graves' disease. J. Clin. Invest. 20:445 1941.
- I 35 Hertz, S., Roberts, A. Radioactive iodine as an indicator in thyroid physiology. V. Use of radioactive iodine in the differential diagnosis of 2 types of Graves' disease. J. Clin. Invest. 21:31-32 1942.
- I 36 Hertz, S., Roberts, A. Application of radioactive iodine in therapy of Graves' disease. J. Clin. Invest. 21:624 1942.



- I 37 Hertz, S., Roberts, A. Radioactive iodine in the study of thyroid physiology. VII. The use of radioactive iodine therapy in hyperthyroidism. J. Am. Med. Assoc. 131:81-86 1946
- I 38 Hertz, S., Roberts, A., Evans, R. D. Radioactive iodine as indicator in study of thyroid physiology. Proc. Soc. Exp. Biol. and Med. 38: 510-513 1938.
- I 39 Hertz, S., Roberts, A., Means, J. H., Evans, R. D. Radioactive iodine as an indicator in thyroid physiology; II Iodine collection by normal and hyperplastic thyroids in rabbits. Am. J. Physiol. 128:565-576 1940.
- I 40 Hertz, S., Roberts, A., Salter, W. T. Radioactive iodine as an indicator in thyroid physiology. IV. The metabolism of iodine in Graves' disease. J. Clin. Invest. 21:25-32 1942.
- I 41 Horeau, A., Sue, P. Synthesis of thyroxin labelled with radio-iodine; separation in organs of various iodine products resulting from its decomposition. Bull. Soc. Chem. Biol. 27:483-488 1945.
- I 42 Horn, P. More recent work in the field of insurance medicine. Med. Clin. 36:1003-1005 1940.
- I 43 Ito, H. Experimental study of the effects of iodine on the growth and radioactivity of malignant tumor. VII. The period during which the iodine remains in the body of the rabbit. J. Obstet. and Gynecol. 21:263-266 1938.
- I 44 Keating, F. R. Jr., Rawson, R. W., Peacock, W., Evans, R. D. The collection and loss of radioactive iodine compared with the anatomic changes induced in the thyroid of the chick by the injection of thyrotropic hormone. Endocrinol. 36:137-148 1945.

- I 45 Keston, A. S. The Schardinger enzyme in biological iodinations. J. Biol. Chem. 153:335-336 1944.
- I 46 Keston, A. S., Ball, R. P., Frantz, V. K., Palmer, W. W. Storage of radioactive iodine in a metastasis from thyroid carcinoma. Science 95:362-363 1942.
- I 47 Keston, A. S., Goldsmith, E. D., Gordon, A. S., Charipper, H. A. The effect of thiourea upon the metabolism of iodine by rat thyroid. J. Biol. Chem. 152:241-244 1944.
- I 48 Larson, R. A., Keating, F. R. Jr., Peacock, W., Rawson, R. W. A comparison of the effect of thiouracil and of injected thyrotropic hormone on the collection of radioactive iodine and the anatomic changes induced in the thyroid of the chick. Endocrinol. 36:149-159 1945.
- I 49 Larson, R. A., Keating, R. F. Jr., Peacock, W., Rawson, R. W. The effect of thiouracil on the collection of radioactive iodine by the thyroid of the chick. Endocrinol. 36:160-169 1945.
- I 50 Leblond, C. P. Behavior of radio-iodine in resting and stimulated thyroids. Anat. Rec. 88:285-290 1944.
- I 51 Leblond, C. P. Entrance and fate of iodine in the thyroid gland and in the organism in general. Rev. Canad. Biol. 1:402-453 1942.
- I 52 Leblond, C. P. Localization of newly administered iodine in thyroid gland as indicated by radio-iodine. J. Anat. 77:149-152 1943.
- I 53 Leblond, C. P. Locating iodine in tissues auto-graphically, especially after fixation by freezing and drying. Stain Technol. 18:159-164 1943.
- I 54 Leblond, C. P., Fertman, M. B., Puppel, I. D., Curtis, G. M. Radio-iodine autography in studies of human goitrous thyroid glands. Arch. of Path. 41:510-515 1946.



- I 55 Leblond, C. P., Gross, J., Evans, R. D. Metabolism of radioiodine in the thyroids of rats exposed to high or low temperatures. Am. J. Physiol. 140:671-676 1944.
- I 56 Leblond, C. P., Gross, J., Peacock, W. C., Evans, R. D. Metabolism of radioactive iodine in the thyroid of rats kept at low temperatures. Federation Proc. 2:28-29 1943.
- I 57 Leblond, C. P., Mann, W. Fixation of iodine by thyroids of rats given diets deficient in iodine. Proc. Soc. Exp. Biol. Med. 49: 102-105 1942.
- I 58 Leblond, C. P., Peacock, W. C., Gross, J., Evans, R. D. Iodine metabolism in the thyroid gland after single injections of 5 or 500 micrograms of radioactive iodine to adult rats. Federation Proc. 2:29 1943.
- I 59 Leblond, C. P., Puppel, I. D., Riley, E., Radike, M., Curtis, G. M. Radioiodine and iodine fractionation studies of human goitrous thyroids. J. Biol. Chem. 162:275-285 1946.
- I 60 Leblond, C. P., Süe, P. Influence of hypophysis on the thyroid uptake and general distribution of radioactive iodine. Anat. Rec. 79(Supp):42 1941.
- I 61 Leblond, C. P., Süe, P. Iodine fixation in the thyroid as influenced by the hypophysis and other factors. Am. J. Physiol. 134: 549-561 1941.
- I 62 Leblond, C. P., Süe, P. Passage de l'iode radioactif (I\*128) dans la thyroïde stimulée par l'hormone thyroïdienne de l'hypophyse. Compt. Rend. Soc. Biol. 133:543-545 1940.
- I 63 Leblond, C. P., Süe, P., Chamorro, A. Passage de l'iode radioactif. (I\*128) dans la thyroïde d'animaux sans hypophyse. Compt. Rend. Soc. Biol. 133:540-543 1940.

- I 64 Lein, A. Studies on the fixation of radioactive iodine by the rabbit thyroid. *Endocr.* 32:429-432 1943.
- I 65 Leiter, L., Seidlin, S. M., Marinelli, L. D., Bauman, E. J. Adenocarcinoma of the thyroid with hyperthyroidism and functional metastases I. Studies with thiouracil and radio-iodine. *J. Clin. Endocrinol.* 6:247-261 1946.
- I 66 Leiter, L., Seidlin, S. M., Marinelli, L. D., Baumann, E. J. The effect of thiouracil on hyperthyroidism and on the uptake of radioactive iodine in patients with adenocarcinoma of the thyroid and functioning metastases. *J. Clin. Invest.* 23:941 1944.
- I 67 Lerner, S. R., Chikoff, I. L. The influence of goitrogenic compounds (sulfonamides and their derivatives, thiourea and its derivatives) on respiration of thyroid tissue. *Endocrinol.* 37:362-368 1945.
- I 68 Low-Beer, B. V. A., Lawrence, J. H., Stone, R. S. The therapeutic use of artificially produced radioactive substances (radiophosphorus, radiostrontium, radioiodine, with special reference to leukemia and allied diseases.) *Radiol.* 39:573-597 1942.
- I 69 Mann, W. Biological studies with radioactive and stable isotopes (radioactive iodine and stable nitrogen). Thesis, Univ. of Rochester.
- I 70 Mann, W., Leblond, C. P. Chemical transformation of the iodine fixed by the thyroid gland. *South. Surg.* 11:828-839 1942.
- I 71 Mann, W., Leblond, C. P., Warren, S. L. Iodine metabolism of the thyroid gland. *J. Biol. Chem.* 142:905-912 1942.
- I 72 Marie, P. L. L'iode radioactive en therapie. *Presse med.* 54: 681-682 1946.
- I 73 Marinelli, L. D., Foote, F. W., Hill, R. F., Hocker, A. F. Retention of radioactive iodine in thyroid carcinomas: histopathologic and radio-autographic studies. *Amer. J. Roentgenol. and Rad. Ther.* 58: 17-32 1947.



- I 74 Miller, W. H., Anderson, G. W., Madison, R. K., Salley, D. J. Exchange reactions of diiodotyrosine. *Science* 100:340-341 1944.
- I 75 Morton, M. E. Metabolism of iodine as studied with its radioactive isotope. Thesis, Univ. of Calif. Graduate Div., North. Sect. 1943.
- I 76 Morton, M. E., Chaikoff, I. L. The in vitro formation of thyroxine and diiodotyrosine by thyroid tissue. *J. Biol. Chem.* 144:565 1942.
- I 77 Morton, M. E., Chaikoff, I. L. The formation in vitro of thyroxine and diiodotyrosine by thyroid tissue with radioactive iodine as indicator. *J. Biol. Chem.* 147:1-9 1943.
- I 78 Morton, M. E., Chaikoff, I. L., Reinhardt, W. O., Anderson, E. Radioactive iodine as an indicator of the metabolism of iodine. VI. The formation of thyroxine and diiodotyrosine by the completely thyroidectomized animal. *J. Biol. Chem.* 147:757-769 1943.
- I 79 Morton, M. E., Chaikoff, I. L., Rosenfield, S. Inhibiting effect of inorganic iodide on the formation in vitro of thyroxine and diiodotyrosine by surviving thyroid tissue. *J. Biol. Chem.* 154:381-387 1944.
- I 80 Morton, M. E., Perlman, I., Chaikoff, I. L. Radioactive iodine as an indicator of the metabolism of iodine. III. The effect of thyrotropic hormone on the turnover of thyroxine and diiodotyrosine in the thyroid gland and plasma. *J. Biol. Chem.* 140:603-611 1941.
- I 81 Morton, M. E., Perlman, I., Anderson, E., Chaikoff, I. L. Radioactive iodine as an indicator of the metabolism of iodine. V. The effects of hypophysectomy on the distribution of labeled thyroxine and diiodotyrosine in thyroid gland and plasma. *Endocrinol.* 30:495-501 1942.

- I 82 Myers, W. G. Some applications of atomic energy to diagnosis and therapy. Ohio J. Sci. 46:197-199 1946.
- I 83 Perlman, I., Chaikoff, I. L., Morton, M. E. Radioactive iodine as an indicator of the metabolism of iodine. I. The turnover of iodine in the tissues of the normal animal, with particular reference to thyroid. J. Biol. Chem. 139:433-447 1941.
- I 84 Perlman, I., Morton, M. E., Chaikoff, I. L. Radioactive iodine as an indicator of metabolism of iodine. II. Rates of formation of thyroxine and diiodotyrosine by intact normal thyroid gland. J. Biol. Chem. 139: 449-456 1941.
- I 85 Perlman, I., Morton, M. E., Chaikoff, I. L. Radioactive iodine as an indicator of metabolism of iodine. IV. The distribution of labeled thyroxine and diiodotyrosine in liver, muscle, and small intestine. Endocrinol. 30:487-494 1942.
- I 86 Pierson, P. H. Primary carcinoma of trachea; treatment with intra-tracheal radium; radioactive iodine fails to show thyroid origin. J. Am. Med. Assoc. 126:206-209 1944.
- I 87 Plati, J. T., Strain, W. H., Warren, S. L. Iodinated organic compounds as contrast media for radiographic diagnoses. II. Ethyl esters of iodinated straight and branched chain phenyl fatty acids. J. Am. Chem. Soc. 65:1273-1276 1943.
- I 88 Puppel, I. D., Leblond, C. P., Curtis, G. M. The surgical therapeutic significance of the functional behavior of thyroid nodules. Ann. Surg. 125:257-281 1947.
- I 89 Rawson, R. W., Evans, R. D., Means, J. H., Peacock, W. C., Lerman, J., Cortell, R. E. The action of thiouracil upon the thyroid gland in



- Graves' disease. J. Clin. Endocrinol. 4:1 1944.
- I 90 Rawson, R. W., Hertz, S., Means, J. H. Thiocyanate goitre in man. Ann. Int. Med. 19:829 1943.
- I 91 Rawson, R. W., Tannheimer, J. F., Peacock, W. The uptake of radioactive I by the thyroids of rats made goiterous by potassium thiocyanate and by thiouracil. Endocrinol. 34:245-253 1944.
- I 92 Reid, A. F., and Keston, A. S. Long-life radioactive iodine. Phys. Rev. 70:987-988 1946.
- I 93 Reiner, L., Lang, E. H., Irvine, J. W., Peacock, W., Evans, R. D. The absorption rates of insulin, globin insulin, and protamine zinc insulin labeled with radioactive iodine. J. Pharmacol. and Exper. Ther. 78:352-357 1943.
- I 94 Reiner, L., Keston, A. S., Green, M. The absorption and distribution of insulin labeled with radioactive iodine. Science 96: 362-363 1942.
- I 95 Reinhardt, W. O. Method for determining completeness of thyroidectomy using radioactive iodine. Proc. Soc. Exper. Biol. and Med. 50:81-84 1942.
- I 96 Rhoads, C. P. Medical uses of atomic energy. United Nations Atomic Energy Commission, Vol. V, 1946.
- I 97 Root, H. F., and others. Absorption of insulin labeled with radioactive iodine in human diabetes. J. Am. Med. Assoc. 124:84-90 1944.
- I 98 Sacks, J. Iodoacetic acid in anaerobic muscular contraction. Am. J. Physiol. 126:388 1939.
- I 99 Salter, W. T., McKay, E. A. Iodine in blood and thyroid of man and small animals. Endocrinol. 35:380-390 1944.

- I 100 Schachner, H., Franklin, A. L., Chaikoff, I. L. The effect of cytochrome oxidase inhibitors on the formation in vitro of thyroxine and diiodotyrosine by thyroid tissue with radioactive iodine as indicator. *J. Biol. Chem.* 151:191-199 1943.
- I 101 Schachner, H., Franklin, A. L., Chaikoff, I. L. On in vitro accumulation of inorganic iodide by surviving thyroid tissue with radioactive iodine as indicator. *Endocrinol.* 34:159-167 1944.
- I 102 Scow, R. O. Effect of growth hormone in rats thyroidectomized at birth. *Anat. Rec.* 88:456 1944.
- I 103 Scow, R. O. Retarding effects of brief refrigeration upon skeletal development in the newborn rat. *Anat. Rec.* 88:457 1944.
- I 104 Scow, R. O., Simpson, M. E. Thyroidectomy in the newborn rat. *Anat. Rec.* 91:209 1945.
- I 105 Seidlin, S. M., Marinelli, L. D. Therapeutic effect of radioactive iodine on adenocarcinoma of the thyroid with functioning metastases. *Bull. N. Y. Acad. Med.* 21:440 1945.
- I 106 Seidlin, S. M., Marinelli, L. D., Oshry, E. Radioactive iodine therapy effect on functioning metastases of adenocarcinoma of the thyroid. *J. Am. Med. Assoc.* 132:838-847 1946.
- I 107 Smith, P. K., Eisenman, A. J., Winkler, A. W. The permeability of human erythrocytes to radioactive chloride, and to bromide and iodide. *J. Biol. Chem.* 141:556-561 1941.
- I 108 Strain, W. H., Plati, J. T., Warren, S. L. Iodinated Organic compounds as contrast media for radiographic diagnoses. I. Iodinated aracyl esters. *J. Am. Chem. Soc.* 64:1436-1440 1942.
- I 109 Süe, Pierre. Application of radioactive indicators in chemistry and biology. *J. Chem. Phys.* 40:17-24 1943.



- I 110 Süe, Pierre Application to chemistry and biology of radioactive indicators. J. Chem. Phys. 38:31-45 1941.
- I 111 Süe, Pierre. Chemical and biological applications of radioactive indicators. II. Preparation of radioactive iodine  $^{128}_{53}\text{I}$  and estimation of its activity. J. Chem. Phys. 38:123-143 1943.
- I 112 Süe, Pierre Preparation of iodine, iodates, and diiodotyrosine from radioactive  $^{128}_{53}\text{I}$ . Exchange reaction of the iodine atoms between iodates, diiodotyrosine, thyroxine, and sodium iodide. Compt. Rend. Soc. Biol. 212:237-238 1941.
- I 113 Taurog, A., Chaikoff, I. L. On the determination of plasma iodine. J. Biol. Chem. 163:313-322 1946.
- I 114 Taurog, A., Chaikoff, I. L., Franklin, A. L. The structural specificity of sulfanilamide-like compounds as inhibitors of the in vitro conversion of inorganic iodide to thyroxine and diiodotyrosine by thyroid tissue. J. Biol. Chem. 161:537-543 1945.
- I 115 Wolff, J., Chaikoff, I. L., Taurog, A., Rubin, L. The disturbance in iodine metabolism produced by thiocyanate: The mechanism of its goitrogenic action with radioactive iodine as indicator. Endocrinol. 39:140-148 1946.

## IRON

- Fe 1     Aub, J.C., Evans, R.D., Gibson, J.G.     Circulating red cell volume in shock; blood preservation Committee on Med. Res. of the Office of Scientific Research and Development. Interim Report No. 2, Shock No. 32.
- Fe 2     Austoni, M.E., Greenberg, D.M.     Studies in iron metabolism with aid of its artificial radioactive isotope; absorption, excretion, and distribution of iron in rat on normal and iron-deficient diets. J. Biol. Chem. 134: 27-41, 1940.
- Fe 3     Bale, W.F.     Use of artificially produced radioactive elements as tagged atoms in biological research. Radiol. 35:184-91, 1940.
- Fe 4     Balfour, W.M., Hahn, P.F., Bale, W.F., Pommerenke, W.T., Whipple, G.H.     Radioactive iron absorption in clinical conditions: normal, pregnancy, anemia, and hemochromatosis. J. Exptl. Med. 76:15-30, 1942.
- Fe 5     Chapin, M.A., Ross, J.F.     Factors influencing the metabolism of radioactive iron in human subjects. Fed. Proc. 1: No.1, 1942.
- Fe 6     Chapin, M.A., Ross, J.F.     The determination of true cell volume by dye dilution, by protein dilution, and with radioactive iron. The error of centrifuge hematocrit. Am. J. Physiol. 137:447-55, 1942.
- Fe 7     Copp, D.H.     A study of iron metabolism with the aid of the radioactive isotope Fe <sup>55</sup>. Thesis, Univ. of Calif. Grad. Div. Northern Section, 1943.
- Fe 8     Copp, D.H., Greenberg, D.M.     A tracer study of iron metabolism with radioactive iron. I. Methods: absorption and excretion of iron. II. Internal metabolism. J. Biol. Chem. 164:377-387, 1946.



- Fe 9 Cruz, W.O., Hahn, P.F., Bale, W.F., Balfour, W.M. The effect of age on the susceptibility of erythrocyte to hypotonic salt solutions. Radioactive iron as a means of tagging the red blood cell. Am. J. M. Sci. 202:157-63, 1941.
- Fe 10 Cruz, W.O., Hahn, P.F., Bale, W.F. Hemoglobin radioactive iron liberated by erythrocyte destruction (acetylphenylhydrazine) promptly reutilized to form new hemoglobin. Am. J. Physiol. 135:595-9, 1942.
- Fe 11 Dubach, R., Moore, C.V., Minnich, V. Studies in iron transportation and metabolism V. Utilization of intravenously injected radioactive iron for hemoglobin synthesis, and an evaluation of the radioactive iron method for studying iron absorption. J. of Lab. and Clin. Med. 31:1201-1222, 1946.
- Fe 12 Erf, L.A. Secretion of orally administered radio-iron in milk of cows. Proc. Soc. Exp. Biol. and Med. 46:284-7, 1941.
- Fe 13 Ferrebee, J.W., Bigson, J.G., Peacock, W.C. Studies on malarial parasites IV. Some observations regarding the age of the erythrocyte invaded by Plasmodium Vivax. J. Infect. Dis. 78:180-2, 1946.
- Fe 14 Gibson, J.B., Aub, J.C., Evans, R.D. Development of methods of preserving and storing red cells or whole blood for transfusion and evaluation of such methods by means of measuring survival of cells after transfusion by means of radioactive iron. Comm. of Med. Res. of the Office of Scientific Res. and Development, Shock Rept. No. 51, 1944.

- Fe 15 Gibson, J.G., Evans, R.D., Aub, J.C. (1) Bicarbonate Buffered Citrate-Dextrose for cell resuspension. (2) Low volume ACD(Rapport's Formula) for preservation of whole blood. (3) Red cells resuspended in 10% corn syrup and in acidified-citrate dextrose pH 5.1 (Hughes). OSRD (Bimonthly progress report No. 28), 1945.
- Fe 16 Gibson, J.G., Peacock, W.C., Seligman, A.M., Sack, T. Circulating red cell volume measured simultaneously by the radioactive iron and dye methods. J. Clin. Invest. 25:(6)838-847, 1946.
- Fe 17 Gibson, J.G., Seligman, A.M., Peacock, W.C., Fine, J. Aub, J.C., Evans, R.D. The circulating red cell and plasma volume and the distribution of blood in large and minute vessels in experimental shock in dogs, measured by radioactive isotopes of iron and iodine. J. Clin. Invest. 26:(1)126-144, 1947.
- Fe 18 Gibson, J.G., Seligman, A.M., Peacock, W.D., Aub, J.C., Fine, J. Evans, R.D. The distribution of red cells and plasma in large and minute vessels of the normal dog, determined by radioactive isotopes of iron and iodine. J. Clin. Invest. 25(6):848-857, 1946.
- Fe 19 Gibson, J.G., Weiss, S., Evans, R.D., Peacock, W.C., Irvine, J.W. Good, W.M., Kip, A.F. The measurement of the circulating red cell volume by means of two isotopes of iron. J. Clin. Invest. 25(4):616-626, 1946.
- Fe 20 Goetsch, A.T., Moore, C.V., Minnich, V. Observations on the effect of massive doses of iron given intravenously to patients with hypochromic anemia. Blood, The J. of Hematology 1:129-142, 1946.



- Fe 21 Greenberg, D.M., Copp, D.H., Cuthbertson, E.M. Studies in mineral metabolism with the aid of artificial radioactive isotopes VII The distribution and excretion, particularly by way of the bile, of iron, cobalt and manganese. J. Biol. Chem. 147:749-56, 1943.
- Fe23 Greenberg, G.R., Wintrobe, M.M. A labile iron pool, J. Biol. Chem. 165:397, 1946.
- Fe 24 Hahn, P.F. Chart for estimation of red cell mass of dogs from jugular hematocrit value and body weight. Am. J. Physiol. 141:363-4, 1944.
- Fe 25 Hahn, P.F. Radioactive iron procedures; purification, electroplating and analysis. Ind. and Engin. Chem. 17:45-46, 1945.
- Fe 26 Hahn, P.F. A simple method of preparation of colloidal ferrous iron for intravenous administration. J. Biol. Chem. 163:435, 1946.
- Fe 27 Hahn, P.F., Bale, W.F., Hettig, R.Q., Kamen, M.D., Whipple, G.H. Radioactive iron and its excretion in urine, bile and feces. J. Exper. Med. 70:443-51, 1939.
- Fe 29 Hahn, P.F., and others. Red cell and plasma volumes (circulating and total) as determined by radio iron and by dye. J. Exper. Med. 75:221-32, 1942.
- Fe 30 Hahn, P.F., Balfour, W.M., Ross, J.F., Bale, W.F., Whipple, G.H. Red cell volume circulating and total as determined by radio iron. Science 93:87-8, 1941.

- Fe 31 Hahn, P.F., Bale, W.F. Linear relationship between the circulating red cell mass and the venous hematocrit as determined with radioactive iron. *Am. J. Physiol.* 136:314-7, 1942.
- Fe 32 Hahn, P.F., Bale, W.F., Balfour, W.M. Radioactive iron used to study red blood cells over long periods; the constancy of the total blood volume in the dog. *Am. J. Physiol.* 135:600-5, 1942.
- Fe 33 Hahn, P.F., Bale, W.F., Bonner, J.F., Jr. Mechanism of the effect of epinephrine on the venous hematocrit value of the normal unanesthetized dog. *Am. J. Physiol.* 137:No. 4 717-721, 1942.
- Fe 34 Hahn, P.F., Bale, W.F., Bonner, J.F., Jr. Removal of red cells from the active circulation by sodium pentobarbital. *Am. J. Physiol.* 138:415-20, 1943.
- Fe 35 Hahn, P.F., Bale, W.F., Lawrence, E.O., Whipple, G.H. Radioactive iron and its metabolism in anemia. *J.A.M.A.*, 111:2285-6, 1938.
- Fe 36 Hahn, P.F., Bale, W.F., Lawrence, E.O., Whipple, G.H. Radioactive iron and its metabolism in anemia; its absorption, transportation and utilization. *J. Exper. Med.* 69:739-53, 1939.
- Fe 37 Hahn, P.F., Bale, W.F., Ross, J.F., Balfour, W.M., Whipple, G.H. Radioactive iron absorption by gastro-intestinal tract. Influence of anemia, anoxide, and antecedent feeding. Distribution in growing dogs. *J. Exper. Med.* 78:169-88, 1943.
- Fe 38 Hahn, P.F., Bale, W.F., Ross, J.F., Hetting, R.A., Whipple, G.H. Radio-iron in plasma does not exchange with hemoglobin iron in red cells. *Science* 92:131-2, 1940.
- Fe 39 Hahn, P.F., Bale, W.F., Whipple, G.H. Effects of inflammation (turpentine abscess) on iron absorption. *Proc. Soc. Exp. Biol. and Med.* 61:405-406, 1946.



- Fe 40 Hahn, P.F., Granick, S., Bale, W.F., Michaelis, L. Ferritin; VI  
Conversion of inorganic and hemoglobin iron into ferritin iron in  
the animal body. Storage function of ferritin iron as shown by  
radioactive and magnetic measurements. J. Biol. Chem. 150:407-12,  
1943.
- Fe 41 Hahn, P.F., Jonas, E., Lowe, R.C., Meneely, G.N., Peacock, W. The  
relative absorption and utilization of ferrous and ferric iron in  
anemia as determined with the radioactive isotope. Am. J. Physiol.  
143:191-7, 1945.
- Fe 42 Hahn, P.F., Lowe, R.C., Meneely, G.K., Bale, W.F. Relative uti-  
lization of ferrous and ferric radioactive iron in clinical and  
experimental anemia. Federation Proc. 3:89, 1944.
- Fe 43 Hahn, P.F., Miller, L.L., Robscheit-Robbins, F.S., Bale, W.F.,  
Whipple, G.H. Peritoneal absorption - red cells labeled by ra-  
dio-iron hemoglobin move promptly from peritoneal cavity into the  
circulation. J. Exper. Med. 80:77-82, 1944.
- Fe 44 Hahn, P.F., Ross, J.F., Bale, W.F., Whipple, G.H. Utilization  
of iron and rapidity of hemoglobin formation in anemia due to blood  
loss, J. Exper. Med. 71:731-6, 1940.
- Fe 45 Hahn, P.F., Whipple, G.H. Hemoglobin production in anemia limit-  
ed by low protein intake. Influence of iron intake, protein supple-  
ments and fasting. J. Exper. Med. 69:315-326, 1939.
- Fe 46 Hahn, P.F., Whipple, G.H. The use of radioactive iron in study  
of problems of iron metabolism and experimental anemia. J. App.  
Physics. 12:314, 1941.
- Fe 47 Hamilton, J.G. The use of radioactive tracers in biology and  
medicine. Radiology 39:541-72, 1942.

- Fe 48 Hawkins, W.B., Hahn, P.F. Biliary excretion of radioactive iron and total iron as influenced by red cell destruction. J. Exp. Med. 80:31-8, 1944.
- Fe 49 Miller, L.L., Hahn, P.F. The appearance of radioactive iron as hemoglobin in the red cell; the significance of "easily split" iron. J. Biol. Chem. 134:585-90, 1940.
- Fe 52 Moore, C.V., Minnich, V., Welch, J. Studies in iron transportation and metabolism. III. The normal fluctuations of serum and "easily split-off" blood iron in individual subjects. J. Clin. Invest. 18:543-552, 1939.
- Fe 50 Moore, C.V., Arrowsmith, W.R., Welsh, J., Minnich, V. Studies in iron transportation and metabolism. IV. Observations on the absorption of iron from the gastro-intestinal tract. J. of Clin. Invest. 18:553-580, 1939.
- Fe 51 Moore, C.V., Dubach, R., Minnich, V., Roberts, H.K. Absorption of ferrous and ferric radioactive iron by human subjects and by dogs. J. Clin. Inv. 23:755-67, 1944.
- Fe 53 Myers, W.G. Some applications of atomic energy to diagnosis and therapy. Ohio J. Sci. 46(4):197-199, 1946.
- Fe 54 Peacock, W.C., Evans, R.D., Irvine, J.W. Jr., Good, W.M., Kip, A.F. Weiss, S., Gibson, J.G. The use of two radioactive isotopes of iron in tracer studies of erythrocytes. J. Clin. Invest. 25(4): 605-615, 1946.
- Fe 55 Pommerenke, W.T., Hahn, P.F., Bale, W.F., Balfour, W.M. Transmission of radioactive iron to the human fetus. Am. J. Physiol. 137: 164-70, 1942.



- Fe 56 Ross, J.F. Radioactive iron in experimental medicine. Bull. New Engl. M. Center 4:220-223, 1942.
- Fe 57 Ross, J.F., Chapin, M.A. The absence of erythrocyte reserves in human subjects as indicated with radioactive tagged cells. J. Clin. Invest. 21:640-641, 1942.
- Fe 58 Ross, J.F., Chapin, M.A. The direct determination of erythrocyte volume in human subjects with radioactively tagged cells. Fed. Proc. Vol. No. 1, 1942.
- Fe 59 Ross, J.F., Chapin, M.A. Effect of storage of citrated blood on the survival of transfused erythrocytes. J.A.M.A. 123:827-829, 1943.
- Fe 60 Ross, J.F., Chapin, M.A. The electrolytic separation of radioactive iron from the blood. Rev. Scientific Instruments. 13:77-80, 1942.
- Fe 61 Waring, W.S., Werkman, C.H. Iron deficiency in bacterial metabolism. Arch. Biochem 4:75-87, 1944.
- Fe 62 Wintrobe, M.M., et al. The anemia of infection III. The uptake of radioactive iron in iron-deficient and in pyridoxine-deficient pigs before and after acute inflammation. J. Clin. Invest. 26(1): 103-113, 1947.
- Fe 63 Yoshikawa, H., Hahn, P.F., Bale, W.F. The form of combination of radioactive iron and copper in plasma following ingestion. Proc. Soc. Exper. Biol. and Med. 4:285-289, 1942.

# Addendum

- Fe 64 Gibson, J. G., 2nd, Aub, J. C., Evans, R. D., Peacock, W. C., Irvine, J. W. Jr., Sack, T. The measurement of post-transfusion survival of preserved stored human erythrocytes by means of two isotopes of radioactive iron. J. Clin. Invest. 26:704-714 1947.
- Fe 65 Gibson, J. G., 2nd, Evans, R. D., Aub, J. C., Sack, T., Peacock, W. C. The post-transfusion survival of preserved human erythrocytes stored as whole blood or in resuspension, after removal of plasma, by means of two isotopes of radioactive iron. J. Clin. Invest. 26:715-738 1947.
- Fe 66 Gibson, J. G., 2nd, Peacock, W. C., Evans, R. D., Sack, T., Aub, J. C., The rate of post-transfusion loss of non-viable stored human erythrocytes and the reutilization of hemoglobin-derived radioactive iron. J. Clin. Invest. 26:739-746 1947.
- Fe 67 Gibson, J. G., 2nd, Sack, T., Evans, R. D., Peacock, W. C. The effect of varying temperatures on the post-transfusion survival of whole blood lost during depot storage and after transportation by land and air. J. Clin. Invest. 26:747-755 1947.
- Fe 68 Ross, J. F., Finch, C. A., Peacock, W. C., Sammons, M. E. The in vitro preservation and post-transfusion survival of stored blood. J. Clin. Invest. 26: 687-703 1947.
- Fe 69 Strumia, M. M., Blake, A. D., Wicks, W. A. The preservation of whole blood. J. Clin. Invest. 26:667-671 1947.
- Fe 70 Balfour, W. M. Factors regulating the absorption of iron in dogs as measured with the radioactive isotope. Am. J. Path. 17:438 1941.



## KRYPTON

- Kr 1 Cook, S.F., Sears, W.F. Studies on the cardio-vascular system of dogs with radioactive inert gases. Am. J. Physiol. 144: 164-7 1945.
- Kr 2 Jones, H., Dobson, E., Lawrence, J. Tracer studies on blood-tissue perfusion rates at rest and a new criterion of blood mixing times. Abst. Comm., XVII Internat. Physiol. Cong. pp. 28-9 1947.
- Kr 3 Lawrence, J.H., Loomis, W.F., Tobias, C.A., Turpin, F.H. Preliminary observations on the narcotic effect of xenon with a review of values for solubilities of gases in water and oils. J. of Physiol. 105: 197-204 1946.
- Kr 4 Morales, M.F., Smith, R.E. The physiological factors which govern inert gas exchange. Bull. Math. Biophys. 7: 99-106 1945.

## LANTHANUM

- La 1      Hamilton, J. G. The metabolism of the fission products and the heaviest elements. Radiology 49: 325-43, 1947.



## LEAD

- Pb 1 Behrens, B., Pachur, R. Zur Pharmakologie des Bleies; die Verteilung und der Zustand kleinster Bleimengen im Blut. Arch. Exper. Pathol. und Pharmacol. 122: 319-37 1927
- Pb 2 Black, Charles E. Commercial lead as a possible inciting factor in bronchiogenic carcinoma (2 cases). Arch. Path. 35: 366 1943
- Pb 3 Christiansen, I.A., Hevesy, G., Lomholt, S. Recherches, par une méthode radiochimique, sur la circulation du plomb dans l'organisme. Compt. Rend. Acad. Sci. 179: 291-2 1924
- Pb 4 Crandall, L.A., Jr, Murer, H.K. Effect of pectin on retention of dietary lead (radium D). J. Nutrit. 23: 239-58 1942
- Pb 5 Dittmar, C. Über die Verteilung radioaktiver Substanzen in Körper von Tumormäusen nach Injektion von Thorium B - haltigen Lösungen. Zeitschr. Krebsforsch. 48: 121-8 1938
- Pb 6 Hevesy, G. The absorption of lead by plants. Biochem. J. 17: 439 1923
- Pb 7 Mortensen, R.A. The absorption of lead tetraethyl with radioactive lead as indicator. J. Indust. Hyg. and Toxicol. 24: 285-8 1942
- Pb 8 Mortensen, R.A., Kellog, K.E. The uptake of lead by blood cells as measured with a radioactive isotope. J. Cell. and Comp. Physiol. 23: 11-20 1944

## LITHIUM

- Li 1      Zahl, P. A., Cooper, F. S. Localization of lithium in tumor tissue as a basis for slow neutron therapy. Science 93: 64-5 1941.
- Li 2      Zahl, P.A., Cooper, F.S., Dunning, J. R. Some in vivo effects of localized nuclear disintegration products on a transplantable mouse sarcoma. Proc. Nat. Acad. Sci. 26: 594-98, 1940.



## MAGNESIUM

Mg 1 Ruben, S., Fenkel, A. W., Kamen, M. D. Some experiments on chlorophyll and photosynthesis using radioactive tracers. J. Phys. Chem. 46: 710-714, 1942.

# MANGANESE

- Mn 1 Born, H. J., Timoféeff-Ressowsky, H. A., Wolf, P. M. Versuche über die Verteilung des Mangans im tierischen Organismus mit  $^{56}_{25}\text{Mn}$  als Indikator. Naturwissenschaften 31:246-247 1943.
- Mn 2 Cooper, E. R. Distribution of radioactive Mn in apple trees. New Zeal. Dept. Sci. Ind. Research Ann. Rept. 14:69-71 1940.
- Mn 3 Greenberg, D. M. Tracer studies with radioactive isotopes of the metabolism of calcium and manganese in the animal organism. J. App. Physics 12:318 1941.
- Mn 4 Greenberg, D. M., Campbell, W. W. Studies in mineral metabolism with the aid of induced radioactive isotopes; IV. Manganese Proc. Nat. Acad. Sci. 26:448-452 1940.
- Mn 5 Greenberg, D. M., Copp, D. H., Cuthbertson, E. M. Studies in mineral metabolism with the aid of artificial radioactive isotopes. VII. The distribution and excretion, particularly by way of the bile, of iron, cobalt and manganese. J. Biol. Chem. 147:749-756 1943.
- Mn 6 Hahn, P. F., Sheppard, C. W. Selective radiation obtained by the intravenous administration of colloidal radioactive isotopes in diseases of the lymphoid system. South. Med. Jour. 39:558-562 1946.
- Mn 7 Mohamed, M. S., Greenberg, D. M. A tracer study with  $\text{Mn}^{56}$  on chicks with perosis produced by a synthetic manganese-deficient diet. Proc. Soc. Exp. Biol. Med. 54:197-200 1943.
- Mn 8 Schreiner, O. W. Brucellosis; preliminary report of cases treated with radioactive colloidal manganese. Indust. Med. 12:840-842 1943.
- Mn 9 Sheppard, C. W. and Hahn, P. F. Retention and excretion of manganese dioxide dispersions administered intravenously to humans. South. Med. Jour. 39:562-565 1946.



## MERCURY

- Hg 1 Goodman, C., Irvine, J. W., Jr., Horan, C. F. Mercury vapor measurement; a radioactive method. J. Ind. Hyg. & Toxicol. 25:275-281, 1943

## NEPTUNIUM

- Np 1      Hamilton, J. G. The metabolism of the fission products  
and the heaviest elements. Radiology 49: 325-43, 1947.



## NITROGEN

- N 1 Barnes, Frederick Walter, Jr. On the biological synthesis of purines and pyrimidines. Dissertation - Thesis, Columbia Univ., New York, 1943
- N 2 Barnes, F. W., Jr. Schoenheimer, R. On the biological synthesis of purines and pyrimidines. J. Biol. Chem. 151:123-39, 1943
- N 3 Behrens, O. K., Lipmann, F., Cohn, M. and Burk, D. The non-specificity of amino acid configuration in malignant tissue hydrolysates. Science 92:32-34, 1940
- N 4 Bloch, K., Schoenheimer, R. The biological demethylation of sarcosine to glycine. J. Biol. Chem. 135:99, 1940
- N 5 Bloch, K., Schoenheimer, R. The biological formation of creatine. J. Biol. Chem. 133:633, 1940
- N 6 Bloch, K., Schoenheimer, R. The biological origin of the amidine group in creatine. J. Biol. Chem. 134:785, 1943
- N 7 Bloch, K., Schoenheimer, R. The biological precursors of creatine. J. Biol. Chem. 138:167-194, 1941
- N 8 Bloch, K., Schoenheimer, R. Studies in protein metabolism; XI The metabolic relation of creatine and creatinine studied with isotopic nitrogen. J. Biol. Chem. 131:111-19, 1939
- N 9 Bloch, D., Schoenheimer, R., Rittenberg, D. Rate of formation and disappearance of body creatine in normal animals. J. Biol. Chem. 138:155-166, 1941
- N 10 Boxer, G. E., Stetten, DeW., Jr. The effect of dietary choline upon the rate of turnover of phosphatide choline. J. Biol. Chem. 153:617-625, 1944

- N 11 Burris, R. H. Distribution of isotopic nitrogen in Azotobacter vinelandii. J. Biol. Chem. 143:509-17, 1942
- N 12 Burris, R. H. Failure of barley to fix molecular N<sup>15</sup>. Science 94:238-239, 1941
- N 13 Burris, R. H., Miller, C. E. Application of N<sup>15</sup> to the study of biological nitrogen fixation. Science 93:114-115, 1941
- N 14 Burris, R. H., Eppling, F. J., Wahlin, H. B., Wilson, P. W. Studies of biological nitrogen fixation with isotopic nitrogen. Soil Sci. Soc. of Amer. 7:258-62, 1942
- N 15 Burris, R. H., Eppling, F. J., Wahlin, H. B., Wilson, P. W. Detection of nitrogen fixation with isotopic nitrogen. J. Biol. Chem. 148:349-57, 1943
- N 16 Burris, R. H. and Wilson, P. W. Comparison of the metabolism of ammonia and molecular nitrogen in Azotobacter. J. Biol. Chem. 165:595, 1946
- N 17 Chargaff, E., Ziff, M., Rittenberg, D. Study of nitrogenous constituents of tissue phosphatides. J. Biol. Chem. 144:343-52, 1942
- N 18 Clutton, R. F., Schoenheimer, R., Rittenberg, D. Studies in protein metabolism; conversion of ornithine into arginine in mouse. J. Biol. Chem. 132:227-31, 1940
- N 19 Committee on Growth. Symposium on the use of isotopes in biological research. March 3 and 4, 1947
- N 20 Fink, R. M., Enns, T., Kimball, C. P., Silberstin, H. E., Bale, W. F., Madden, S. C., Whipple, G. H. Plasma protein metabolism



normal and associated with shock, observations using protein labelled by heavy nitrogen in lysine. J. Exp. Med. 80:455, 1944

- N 21 Foster, G. L. Some amino acid analyses of hemoglobin and beta-lactoglobulin. J. Biol. Chem. 159:431-438, 1945
- N 22 Foster, G. L., Schoenheimer, R., Rittenberg, D. Studies in protein metabolism. V. The utilization of ammonia for amino acid and creatine formation in animals. J. Biol. Chem. 127:319, 1938
- N 23 Graff, S., Rittenberg, D., Foster, G. L. The glutamic acid of malignant tumors. J. Biol. Chem. 133:745-752, 1940
- N 24 Hamilton, J. G. The use of radioactive tracers in biology and medicine. Radiology 39:541-72, 1942
- N 25 Heidelberger, M., and others. Behavior of antibody protein toward dietary nitrogen in active and passive immunity. J. Biol. Chem. 144:555-62, 1942
- N 26 Herbst, R. M., Shemin, D. The synthesis of peptides by transamination. J. Biol. Chem. 147:541-47, 1943
- N 27 Hevesy, G., Linderstrom-Lang, K., Keston, A. S., Olsen, C. Exchange of nitrogen atoms in the leaves of the sunflower. Compt. Rend. Trav. Lab. Carlsberg (Copenhagen) ser. Chem. 23:213-218, 1940
- N 29 Keston, A. S., Rittenberg, D. and Schoenheimer, R. Studies in protein metabolism. IV. The stability of nitrogen in organic compounds. J. Biol. Chem. 127:315-318, 1939

- N 30 Kritsman, M. G., Konikova, A. S. Application of the heavy isotopes of hydrogen and nitrogen in biochemistry. Adv. in Modern. Biol. USSR 15:27-47, 1943
- N 31 Nakaidzumi, M., Murati, K., Miyakawa, S. Result of keeping animals in cyclotron room; damages inflicted on organs and tissues of rabbit by irradiation from cyclotron. Far East Sc. Bull. 3:37, 1943
- N 33 Norman, A. G. and Werkman, C. H. The use of the nitrogen isotope  $N^{15}$  in determining nitrogen recovery from plant materials decomposing in soil. J. Am. Soc. Agronomy 35:1023-1025, 1943
- N 34 Norman, A. G., Werkman, C. H. The use of  $N^{15}$  in determining N recovery from plant materials decomposing in soil. J. Am. Soc. Agron. 35:1023-5, 1944
- N 36 Plentl, A. A., Schoenheimer, R. Studies in the metabolism of purines and pyrimidines by means of isotopic nitrogen. J. Biol. Chem. 153:203-17, 1944
- N 37 Ratner, S. Conversion of d-glutamic acid to pyrrolidonecarboxylic acid by the rat. J. Biol. Chem. 152:559-64, 1944
- N 38 Ratner, S., Rittenberg, D., Keston, A. S., Schoenheimer, R. Studies in protein metabolism XIV. The chemical interaction



- of dietary glycine and body proteins in rats. J. Biol. Chem. 134:665-676, 1940
- N 39 Ratner, S., Schoenheimer, R., Rittenberg, D. Studies in protein metabolism XIII. The metabolism and inversion of d (-) - leucine studied with two isotopes. J. Biol. Chem. 134:653-663, 1940
- N 40 Ratner, S., Weissman, N., Schoenheimer, R. The metabolism of d-lysine investigated with deuterium and heavy nitrogen. J. Biol. Chem. 147:549-56, 1943
- N 41 Rittenberg, D., Keston, A. S., Rosebury, F., Schoenheimer, R. Studies in protein metabolism II. The determination of N isotopes in organic compounds. J. Biol. Chem. 127:291-299, 1939
- N 42 Rittenberg, D., Schoenheimer, R. Studies in protein metabolism VI. Hippuric acid formation studied with the aid of the N isotope. J. Biol. Chem. 127:329, 1939
- N 43 Rittenberg, D., Schoenheimer, R., Keston, A. S. Studies in protein metabolism. IX. The utilization of ammonia by normal rats on a stock diet. J. Biol. Chem. 128:603, 1939
- N 44 Rittenberg, D., and Shemin, D. Isotope technique in the study of intermediary metabolism. Currents in Biochem. Research, pp. 261-276, 1946
- N 45 Ruben, S., Hassid, W. Z., Kamen, M. D. Radioactive nitrogen in the study of  $N_2$  fixation by non-leguminous plants. Science 91:578-579, 1940

- N 46 Schoenheimer, R. The use of organic compounds containing stable isotopes for the study of intermediary metabolism. J. App. Physics 12:322, 1941
- N 47 Schoenheimer, R., and others. Application of nitrogen isotope  $N^{15}$  for study of protein metabolism. Science 88:599-600, 1938
- N 48 Schornheimer, R., Ratner, S. The metabolism of proteins and amino acids. Ann. Rev. Biochem. 10:197-220, 1941
- N 49 Schoenheimer, R., Ratner, S. Studies in protein metabolism III. Synthesis of amino acids containing isotopic N. J. Biol. Chem. 127:301-313, 1939
- N 50 Schoenheimer, R., Ratner, S., and Rittenberg, D. The process of continuous deamination and reamination of amino acids in the proteins of normal animals. Science 89:272-73, 1939
- N 51 Schoenheimer, R., Ratner, S., Rittenberg, D. Studies in protein metabolism; VII The metabolism of tyrosine. J. Biol. Chem. 127:333-44, 1939
- N 52 Schoenheimer, R., Ratner, S., Rittenberg, D. Studies in protein metabolism. X. The metabolic activity of body proteins investigated with 1 (-) - leucine containing two isotopes. J. Biol. Chem. 130:703-732, 1939
- N 53 Schoenheimer, R., Ratner, S., Rittenberg, D., Heidelberger, M. The interaction of antibody protein with dietary nitrogen in actively immunized animals. J. Biol. Chem. 144:545-54, 1942
- N 54 Schoenheimer, R., Ratner, S., Rittenberg, D., Heidelberger, M. The interaction of the blood proteins of the rat with dietary nitrogen. J. Biol. Chem. 144:541-4, 1942



- N 55 Schoenheimer, R., Rittenberg, D., Fox, M., Keston, A. S., Ratner, S. The nitrogen isotope ( $N^{15}$ ) as a tool in the study of the intermediary metabolism of nitrogenous compounds. J. Am. Chem. Soc. 59:1768, 1937
- N 56 Schoenheimer, R., Rittenberg, D., Keston, A. S. Studies in protein metabolism. VIII. The activity of the  $\alpha$ -amino group of histidine in animals. J. Biol. Chem. 127:385-89, 1939
- N 57 Scott, K. G. A comparison of two levels of roentgen and neutron irradiation of normal and lymphomatous mice, using radiophosphorus as an indicator of cellular activity. Radiology 46:173-175, 1946
- N 58 Shemin, D. Amino acid determinations on crystalline bovine and human serum albumen by the isotope-dilution method. J. Biol. Chem. 159:439-43, 1945
- N 59 Shemin, David. The biological conversion of l-serine to glycine. J. Biol. Chem. 162:297-307, 1946
- N 60 Shemin, D. and Rittenberg, D. The biological utilization of glycine for the synthesis of the protoporphyrin of hemoglobin. J. Biol. Chem. 166:621, 1946
- N 61 Shemin, D., Rittenberg, D. Evidence for the totally asymmetric synthesis of amino acids in vivo. J. Biol. Chem. 151:507-10, 1943
- N 62 Shemin, D., Rittenberg, D. On the mechanism of the conversion of ornithine to proline in vivo; intramolecular nitrogen shift. J. Biol. Chem. 158:71-76, 1945
- N 63 Shemin, D., Rittenberg, D. Some interrelations in general N metabolism. J. Biol. Chem. 153:401-21, 1944

- N 64 Shemin, D. and Rittenberg, D. The life span of the human red blood cell. J. Biol. Chem. 166:627, 1946
- N 65 Shemin, D., Rittenberg, D. The utilization of glycine for the synthesis of a porphyrin. J. Biol. Chem. 159:567-568, 1945
- N 66 Stetten, D., Jr. Biological relationships of choline, ethanolamine, and related compounds. J. Biol. Chem. 138:437, 1941
- N 67 Stetten, D., Jr. Biological relationships of choline ethanolamine and related compounds. J. Biol. Chem. 140:143-52, 1941
- N 68 Stetten, D. The fate of dietary serine in the body of the rat. J. Biol. Chem. 144:501-506, 1942
- N 69 Stetten, D., Jr. Biological synthesis of choline by rats on diets with and without lipotropic methyl. J. Biol. Chem. 142:629-633, 1942
- N 70 Stetten, M. R., Schoenheimer, R. The metabolism of L (-) - proline studied with the aid of deuterium and isotopic nitrogen. J. Biol. Chem. 153:113-32
- N 71 Vickery, H. B., Pucher, G. W., Schoenheimer, R., Rittenberg, D. The assimilation of ammonia nitrogen by the tobacco plant: A preliminary study with isotopic nitrogen. J. Biol. Chem. 135:531-539, 1940
- N 72 Vickery, H. B., Pucher, G. W., Schoenheimer, R., Rittenberg, D. The metabolism of nitrogen in the leaves of the buckwheat plant. J. Biol. Chem. 129:791, 1939
- N 73 Vigneaud, V. du, Cohn, M., Brown, G. B., Irish, O. J., Schoenheimer, R., Rittenberg, D. A study of the inversion of D-phenylaminobutyric acid and the acetylation of L-phenylaminobutyric acid by means of the isotopes of nitrogen and hydrogen. J. Biol. Chem. 131:273-296, 1939



- N 74 Vigneaud, V. du, Simmonds, S., Chandler, J. P., Cohn, M. A further investigation of the role of betaine in transmethylation reactions in vivo. J. Biol. Chem. 165:639-48 1946.
- N 75 Waelsch, H., Rittenberg, D. The metabolism of glutathione. Science 90:423-4 1939.
- N 76 Waelsch, H., Rittenberg, D. Glutathione. I. The metabolism of glutathione studied with isotopic glycine. J. Biol. Chem. 139:761-74 1941.
- N 77 Waelsch, H., Rittenberg, D. Glutathione. II. The metabolism of glutathione studied with isotopic ammonia and glutamic acid. J. Biol. Chem. 144:53-8 1942.
- N 78 Weissman, N., Schoenheimer, R. Studies in protein metabolism. XV. The relative stability of l (+) - lysine in rats studied with deuterium and heavy nitrogen. J. Biol. Chem. 140:779-95 1941.
- N 79 Wilson, P. W., Hull, J. F., Burris, R. H. Competition between free and combined nitrogen in nutrition of Azotobacter. Proc. Nat. Acad. Sci. U. S. 29:289-94 1943.

#### Addendum

- N 80 Barnes, F. W., Jr., Schoenheimer, R. On the biological synthesis of purines and pyrimidines. J. Biol. Chem. 151:123-39 1943.
- N 81 Schoenheimer, R. The dynamic state of body constituents. 81 pp. 1942.

## OXYGEN

- O 1 Barnes, T. C. and Jahn, T. L. Properties of water of biological interest. *Quart. Rev. of Biol.* 9:292-341, 1934.
- O 2 Committee on Growth. Symposium on the use of isotopes in biological research. March 3 and 4, 1947 (mimeographed).
- O 3 Dole, M., Hawkings, R. C., Barker, H. A. Bacterial fractionation of oxygen isotopes. *Am. Chem. Soc.* 69: 226-228, 1947.
- O 4 Dole, M., Jenks, G. Isotopic composition of photosynthetic oxygen. *Science* 100: 409, 1944.
- O 5 Kamen, M. D., Survey of contemporary knowledge of biogeochemistry. 1. Isotopic phenomena in biogeochemistry. *Bull. Am. Mus. Nat. Hist.* 87: 105-138, 1946.
- O 6 Kamen, M. D., Barker, H. A. Inadequacies in present knowledge of the relation between photosynthesis and the O 18 content of atmospheric oxygen. *Proc. Nat. Acad. Sci.* 31: 8-15, 1945.
- O 7 Ruben, S., Randall, M., Kamen, M., Hyde, J. L. Heavy oxygen (O 18) as tracer in the study of photosynthesis. *J. Amer. Chem. Soc.* 63: 877-879, 1941.



## PHOSPHORUS

- P 1 Abels, J. C., Kenney, J. M., Craver, L., Marinelli, L. D., Rhoads, C. P. Postirradiation changes in the levels of organic phos in the blood of patients with leukemia. Cancer Res. 1: 771, 1941
- P 2 Ahlström, L., Euler, H. v., and Hevesy, G. v. Bildung von Nukleinsäure in Sarkomschnitten. Arkiv för Kemi, Mineralogi och Geologi. Band 21A pp. 1-15, 1945
- P 3 Ahlström, L., Euler, H. v. and Hevesy, G. Die Wirkung von Röntgenstrahlen auf den Nukleinsäureumsatz in den Organen der Ratte. Arkiv för Kemi, Mineralogi och Geologi, Band 19A, no. pp. 1-16, 1944
- P 4 Ahlström, L., Euler, H. v. and Hevesy, G. v. Über die indirekte Wirkung von Röntgenstrahlen auf das Jensensarkom. Arkiv for Kemi, Mineralogi och Geologi, Band 19A, pp. 1-16, 1944
- P 5 Ahlström, L., Euler, H. v. and Hevesy, G. v. Über die kurzlebige durch Röntgenstrahlen bewirkte Hemmung der Nukleinsäurebildung.. Arkiv for Kemi, Mineralogi och Geologi, Band 18B, pp. 1-17, 1944
- P 6 Ahlström, L., Euler, H. v. and Hevesy, G. Turnover of nucleic acid in retrograde sarcomata. Arkiv for Kemi, Mineralogi och Geologi, Band 24A, pp. 1-20, 1946

- P 8 Ahlström, L. H., Euler, v., Hevesy, G. and Zerahn, K. Attempts to find products blocking nucleic acid formation in the circulation of an irradiated organism. Arkiv. Kemi., Min. och Geol. 23A No. 10: 1-6, 1947.
- P 9 Ahlstrom, L., Euler, H., Hevesy, G. and Zerahn, K. Fate of the nucleic acid introduced into the circulation. Arkiv för Kemi, Mineralogi Och Geologi Band 22-A No. 7: 1-10, 1945.
- P 10 Aird, R. B., Cohn, W. E., Weiss, S. Convulsive action of triphenylphosphite. Proc. Soc. Exper. Biol. & Med. 45:306-9, 1940
- P 11 Allen, H., Hemplemann, L. H., Novack N. A. The effect of insoluble  $\text{Rd.P}(\text{CrPO}_4)$  when applied interstitially in the treatment of mammary adenocarcinoma in mice. Cancer Res. 5:239-46, 1945
- P 12 Anderson, R. S. Use of radioactive phos for determining circulating erythrocyte volumes. Am. J. Physiol. 137:539-43, 1942
- P 13 Andreasen, Erik, Ottesen, Jens, Lymphocyte production. The nucleic acid turnover in the lymphoid organs. Acta Physiol. Scand. 10:258-70, 1946
- P 14 Armstrong, W. D. In vitro experiments on exchange of phosphate by enamel and dentin. Proc. Soc. Exper. Biol. Med. 44:28-30, 1940
- P 15 Armstrong, W. D. Radioactive calcium and phosphorus uptake by calcified tissues. J. Dental Res. 24:192, 1945
- P 16 Arnon, D. I., Stout, P. R., Sipos, F. Radioactive phos as an indicator of phos absorption of tomato fruits at various stages of development. Am. J. Bot. 27:791-798, 1940



- P 17 Artom, C. Phospholipid metabolism in denervated muscles. J. Biol. Chem. 139:953-961, 1941
- P 18 Artom, C., Freeman, J. A. Individual phospholipids in plasma of rabbits after fatty meals. J. Biol. Chem. 135:59, 1940
- P 19 Artom, C., Perrier, C., Santangelo, M., Sarzana, G., Segre, E. Distribuzione e velocita di organificazione del fosforo nei vari tessuti animali. Arch. Ital. di Scienze Farmacologiche 15:1-10, 1937
- P 20 Artom, C., Sarzana, G., Perrier, C., Santangelo, M., Segre, E. Influenza della natura della dieta sulla velocita di sintesi dei fosfolipidi nei differenti tessuti. (Ricerche preliminari) La Ricerca Scientifica 2:3-4, 1937
- P 21 Artom, Sarzana, Perrier, Santangelo, Segre, Phospholipid synthesis during fat absorption. Nature 139:1105, 1937
- P 22 Artom, Sarzana, Perrier, Santangelo, Segre, The rate of "organification" of P in animal tissues. Nature 139:836, 1937
- P 23 Artom, C., Sarzana, G., Segre, E. Influence des graisses alimentaires sur la formation des phospholipides dans les tissus animaux. (Nouvelles recherches) Arch. Internat. Physiol. 47:245-276, 1938
- P 24 Aten, A. H. W., Hevesy, G. Diffusion of phosphate ions into blood corpuscles. Nature 142:871, 1938
- P 25 Artom, D., Sarzana, G., Perrier, C., Santangelo, M., Segre, E. Synthesis of PL during the absorption of fats. Arch. Intern. Physiol. 45:32, 1937

- P 26 Ballard, S. S., Dean, L. A. Soil studies with radioactive phosphorus: Significance of biological measurements of the retention of applied phosphorus by soils. *Soil Sci.* 52: 173-183, 1941
- P 27 Ballard, S. S. and Dean, L. A. The use of radioactive phosphorus in soil studies. *J. App. Physics* 11:366-70, 1940
- P 28 Barker, S. B., Furchgott, R. F., Shorr, E. Organic phosphate changes in resting cardiac muscle as indicated by radioactivity studies. *Am. J. Physiol.* 133:202-3, 1941
- P 29 Barnum, C. P., Armstrong, W. D. Phosphate equilibrium between plasma and saliva. *Proc. Soc. Exper. Biol. & Med.* 49:40-42, 1942
- P 30 Barnum, C. P., Armstrong, W. D. In vivo and in vitro exchange of phos by enamel and dentin. *Am. J. Physiol.* 135:478-84, 1942
- P 31 Bernhard, Karl. Chemical embryology. Lipide synthesis in the chick embryo. *Helv. Chim. Acta* 24:1094-8, 1941
- P 32 Biddulph, O. Absorption and movement of radiophosphorus in bean seedlings. *Plant Physiol.* 15:131-136, 1940
- P 33 Biddulph, O. Diurnal migration of injected radiophosphorus from bean leaves. *Amer. J. Bot.* 28:348-352, 1941
- P 34 Biddulph, O. Movement of radiophosphorus in bean seedlings. *Science* 89:393-4
- P 35 Biddulph, O. Translocation of radiophos from bean leaves. *Northwest Sci.* 14:38, 1940
- P 36 Biddulph, O. and Brown, D. H. Growth and phosphorus accumulation in cotton flowers as affected by meiosis and fertilization. *Am. J. of Bot.* 32:182-188, 1945



- P 37 Biddulph, O. and Markle, J. Translocation of radiophosphorus in the phloem of the cotton plant. *Am. J. of Bot.* 31:65-70, 1944
- P 38 Blayney, J. R., Wassermann, F., Groetzinger, G., DeWitt, T. G. Further studies in mineral metabolism of human teeth by use of radioactive phos. *J. Dent. Res.* 20:559-63, 1941
- P 39 Bodecker, C. F. Tooth condition, a factor in experimental isotope absorption. *J. Dental Research* 22:281-5, 1943
- P 40 Bollman, J. L. and Flock, E. V. Changes in phosphate of muscle during tourniquet shock. *Am. J. of Physiol.* 142:290-297, 1944
- P 41 Bollman, J. L., Flock, E. V. Phosphate turnover in muscle during shock. *Amer. J. Physiol.* 144:437-443, 1945
- P 42 Bollman, J. D., Flock, E. V. Phosphocreatine & inorganic phosphate in working & resting muscles of rats, studied with radioactive phos. *J. Biol. Chem.* 147:155-65, 1943
- P 43 Bollman, J. L., Flock, E. V. Phospholipids of liver and blood studied with radioactive phosphorus. *Proc. Central Soc. Clin. Res.* 18:23-4, 1945
- P 44 Borell, Ulf, Örström, Ake Metabolism in different parts of the brain, especially in the epiphysis, measured with radioactive phos. *Acta Physiol. Scand.* 10:231-42, 1945
- P 45 Borell, U. and Örström, A. The turnover of phosphate in the pineal body compared with that in other parts of the brain. *Wenner-Gren's Institute, Stockholm* 1946
- P 46 Borell, U., Westman, A. and Örström, A. Studies on the functions of the hypophysial-diencephalic system and of the ovaries by means of radioactive phosphorus. *Karolinska Hospital, Stockholm.*

- P 47 Born, H. J. Versuche mit radioaktivem Phosphor an Ratten. Naturwissenschaften 23:476, 1940
- P 48 Born, H. J., Lang, A., Schramm, G. Marking of tobacco mosaic virus with radiophosphorus. Arch. Ges. Virusforsch. 2:461-79;1943  
Chem. Zentr. I:1290-1, 1944
- P 49 Born H. J., Lang, A., Schramm, G., Zimmer, K. G. Experiments on the marking of tobacco mosaic virus with radioactive phos. Naturwissenschaften 29:222-3, 1941
- P 50 Brewer, A. K., Bramley, A. A radioactive isotope study of the absorption of phosphorus and sodium by corn seedlings. Science 91:269-270, 1940
- P 51 Brown, F. A., Jr., Hempelmann, L. H., Jr. Elman, R. The determination of blood volume with red blood cells containing radioactive phos ( $P^{32}$ ). Science 96:323-4, 1942
- P 52 Brues, A. M., Jackson, E. B., Cohn, W. E. Studies on permeability of tissue cells to phosphorus. J. App. Physics 12:321, 1941
- P 53 Brues, A. M., Rathbun, E. N., Cohn, W. E. Metabolism of tissue cultures: II. Estimation of total growth in tissue culture; growth in incomplete media as a "steady state". J. Cell & Comp. Physiol. 24:155-158, 1944
- P 54 Brues, A. M., Tracy, M. M., Cohn, W. E. Nucleic acids of rat liver and hepatoma; their metabolic turnover in relation to growth. J. Biol. Chem. 155:619-33, 1944
- P 55 Brues, A. M., Tracy, M. M., Cohn, W. E. The relation between nucleic acid and growth. Science 95:558-60, 1942



- P 56 Bulliard, Henri, Grundland, I., Moussa, A. The activity of the phosphorus-radiophosphorus exchange in the phosphatides of the cytoplasm. *Compt. rend.* 208:843-5, 1939
- P 57 Bulliard, H., Grundland, I., Moussa, A. Detection of the phosphorus of the phosphatides of the suprarenals by radioactive phosphorus. *Compt. rend.* 207:745-7, 1938
- P 58 Chaikoff, I. L. The application of labeling agents to the study of phospholipid metabolism. *Physiol. Rev.* 22:291-317, 1943
- P 59 Chaikoff, I. L., Entenman, C., Montgomery, M. L. Mechanism of action of antifatty liver factor of pancreas, its relation to plasma choline. *J. Biol. Chem.* 160:387-395, 1945
- P 60 Changus, G. W., Chaikoff, I. L., Ruben, S. Radioactive phos. as indicator of phospholipid metabolism ; IV The phospholipid metabolism of brain. *J. Biol. Chem.* 126:493-500, 1938
- P 61 Chargaff, Erwin The formation of the phos compounds in egg yolk. *J. Biol. Chem.* 142:505-512, 1942
- P 62 Chargaff, E. Note on the mechanism of conversion of beta-glycerophosphoric acid into the alpha form. *J. Biol. Chem.* 144:455-458, 1942
- P 63 Chargaff, Erwin Synthesis of a radioactive organic compounds alpha-glycerophosphoric acid. *J. Am. Chem. Soc.* 60:1700-1, 1938
- P 64 Chargaff, E. Unstable isotopes. I. The determination of radioactive isotopes in organic material. *J. Biol. Chem.* 128:579-85, 1939
- P 65 Chargaff, E. Unstable isotopes; II The relative speed of formation of lecithin and cephalin in the body. *J. Biol. Chem.* 128:587-95, 1939

- P 66 Chargaff, E., Keston, A. S. The metabolism of aminoethyl-phosphoric acid, followed by means of the radioactive phosphorus isotope. *J. Biol. Chem.* 134:515-22, 1940
- P 67 Chargaff, E., Olson, K. B., Partington, P. F. The formation of phosphatides in the organism under normal & pathological conditions. *J. Biol. Chem.* 134:505-14, 1940
- P 68 Chargaff, E., Ziff, M., Cohen, S. S. The conversion of prothrombin to thrombin followed by means of the radioactive phosphorus isotope. *J. Biol. Chem.* 135:351-2, 1940
- P 69 Chievitz, O., Hevesy, G. Radioactive indicators in the study of phosphorus metabolism in rats. *Nature, London* 136:754, 1935
- P 70 Chievitz, O., Hevesy, G. Studies on the metabolism of phosphorus in animals. *Kgl. Danske Videnskab. Selskab Biol. Medd.* 13:1-24, 1937
- P 71 Cohn, Waldo E. Studies in phosphorus metabolism with the aid of radioactive phosphorus. Thesis, Univ. of Cal. Graduate Div. 1938
- P 72 Cohn, W. E. and Brues, A. M. Metabolism of tissue cultures. III. A method for measuring the permeability of tissue cell to solutes. *J. Gen. Phys.* 28:449-461, 1945
- P 73 Cohn, W. E., Greenberg, D. M. Studies in mineral metabolism with aid of artificial radioactive isotopes; III Influence of vitamin D on phosphorus metabolism of rachitic rats. *J. Biol. Chem.* 130:625-34, 1939
- P 74 Cohn, W. E., Greenberg, D. M. Studies in mineral metabolism with aid of artificial radioactive isotopes; absorption, distribution, and excretion of phosphorus. *J. Biol. Chem.* 123:185-98, 1938



- P 75 Cole, W. H., Nastuk, W. L. Disappearance of radioactive phos from heart blood of Limulus polyphemus. Proc. Soc. Exp. Biol. & Med. 48:151-152, 1941
- P 76 Committee on Growth. Symposium on the use of isotopes in biological research. March 3 and 4, 1947 (Mimeographed)
- P 77 Cook, S. F., Scott, K. G., Abelson, P. The deposition of radio phos in tissues of growing chicks. Proc. Nat. Acad. Sci. 23:528-33, 1937
- P 78 Cooper, A. G. S. Preliminary report on the use of radioactive phosphorus in Australia. Med. J. Australia pp. 104, Jan., 1947
- P 79 Craver, L. F. Treatment of leukemia by radioactive phos Bull. N. Y. Acad. Med. 18:254-62, 1942
- P 81 Das Gupta, N. N., Sen. B. B., Purakayastha, B. C., and Ghoshalo, S. N. Study of phosphorus metabolism in animals and plants by autoradiograph. Sci. and Culture 11:535-36, 1936
- P 82 Dols, M. J. L. Phosphorus metabolism in normal and rachitic chickens with a radioactive phosphorus isotope as an indicator. World's Poultry Congr. & Expos. Proc. 7:136-138,
- P 83 Dols, M. J. L. The total phosphorus and lipin phosphorus in normal and rachitic rats. Acta Brevia Neerland. Physiol. Pharmacol., Microbiol. 8:117-18 Nederland. Tijdschr. Geneeskunde 82:2645-6, 1938
- P 84 Dols, M. J. L., Jansen, B. C. P. Studies on phos metabolism in normal and rachitic rats with a radioactive phosphorus isotope. Proc. Koninklijke Acad. van Wetenschappen te Amsterdam 40:547,

- P 85 Dols, M. J. L., Jansen, Sizoo & Barendregt Formation of lipin P in normal and rachitic rats, with a radioactive P isotope as an indicator. *Nature* 141:77, 1938
- P 86 Dols, M. J. L., Jansen, B.C.P., Sizoo, G. J., Barandregt, F. Studies on phosphorus metabolism in normal and rachitic rats with a radioactive phosphorus isotope. II. The total phosphorus with lipin phosphorus content and the formation of lipin phosphorus. *Proc. Acad. Sci. Amsterdam* 41:997-1003, 1938
- P 87 Dols, Jansen, Sizoo, DeVries Studies on P metabolism in normal and rachitic rats with a radioactive P isotope. *Nature* 139:1068 *Proc. Acad. Sci. Amsterdam* 40:547-58, 1937
- P 88 Dols, M. J. L., Jansen, B. C. P., Sizoo, G. J., Van der Maas, G. J. Distribution of phosphorus in the leg bones of chickens. *Nature* 142:953, 1938
- P 89 Dols, M. J. L., Jansen, B. C. P., Sizoo, G. J., Van der Maas, G. J. Phosphorus metabolism in normal and rachitic chickens with a radioactive isotope III. The distribution of the injected phosphorus in the organs, especially in the different parts of the leg bones. *Proc. Acad. Sci. Amsterdam* 42:2, 1939
- P 90 Dunlap, C. E., Robbins, F. C. Effect of roentgen rays, radium, and radioactive phosphorus on thiamine chloride. *Am. J. Roentg. Rad. Ther.* 50:641-8, 1944
- P 91 Eisenman, A. J., Ott, L., Smith, P. K., Winkler, A. W. A study of the permeability of the human erythrocytes to potassium, sodium and phosphate by the use of radioactive isotopes. *Proc. 34th Ann. Mtg. Am. Soc. Biol. Chem.* Mar. 1940



- P 92 Eisenman, A. J., Ott, L., Smith, P. K., Winkler, A. W. A study of the permeability of human erythrocytes to potassium, sodium and inorganic phosphate by the use of radioactive isotopes. J. Biol. Chem. 135: 1940
- P 93 Eklundh-Ehrenberg, C., Euler, H. and Hevesy, G. Note on the number of pollen grains identified in the fruit of the aspen. Arkiv för Kemi, Mineralogi och Geologi 23B:1-5, 1946
- P 94 Ely, J. O. The determination of the distribution of bacteria in the rat by the use of radioactive isotopes. J. Franklin Institute 232:385-387, 1941
- P 95 Ely, J. O. The distribution of radiophos & radiogold in rats after oral, intraperitoneal & subcutaneous administration. J. Franklin Inst. 230:125-34, 1949
- P 96 Ely, J. O. Distribution in the rat of injected radioactivated bacteria. J. Franklin Institute 234:500-14, 1942
- P 97 Ely, J. O. Distribution in the rat of injected radioactive "muscle shock factor" of Green. J. Franklin Institute 238:378-80, 1944
- P 98 Entenman, C., and others Radioactive phos as indicator of phospholipid metabolism; conversion of phosphate to lipoid phos by tissues of laying and non-laying bird. J. Biol. Chem. 124:795-802, 1938
- P 99 Entenman, C., Chaikoff, I. L., Friedlander, H. D. The influence of ingested choline upon choline-containing and noncholine-containing phospholipides of the liver as measured by radioactive phosphorus. J. Biol. Chem. 162:111-18, 1946

- P 100 Entenman, C., Chaikoff, I. L. and Zilversmit, D. B. Removal of plasma phospholipides as a function of the liver: The effect of exclusion of the liver on the turnover rate of plasma phospholipides as measured with radioactive phosphorus. J. Biol. Chem. 166:15, 1946
- P 101 Entenman, C., Ruben, S., Perlman, I., Lorenz, F. W., Chaikoff, I. L. Radioactive phosphorus as an indicator of phospholipid metabolism. III. The conversion of phosphate to lipoid phosphorus by the tissues of the laying and non-laying bird. J. Biol. Chem. 124:795-802
- P 102 Entenman, C., Taurog, A., Chaikoff, I. L. Determination of choline in phospholipides. J. Biol. Chem. 155:13-18, 1944
- P 103 Erf, L. A. Clinical studies with the aid of radiophosphorus; II. The retention of radiophosphorus by tissues of patients dead of leukemia. Am. J. M. Sc. 203:529-35, 1942
- P 104 Erf, L. A. A note on the effect of dermal & enteral irradiation by radiophos on the blood levels of dogs. Am. J. Med. Sc. 202:650-4, 1941
- P 105 Erf, L. A. Retention of radiophos in whole and aliquot portions of tissues of patient dead of leukemia. Proc. Soc. Exp. Biol. & Med. 47:287-9
- P 106 Erf, L. A. Primary polycythemia; remissions induced by therapy with radiophosphorus. Blood: J. of Hematology 1: 202-208, 1946
- P 107 Erf, L. A. Radiophosphorus as the treatment of choice in primary polycythemia. Am. J. of Med. 1:362-366, 1946



- P 108 Erf, L. A., Friedlander, G. Phosphorus exchange in tissues of patients with lymphoid leukemia. *Proc. Soc. Exp. Biol. and Med.* 47:134-6, 1941
- P 109 Erf, L. A., Jones, H. W. Radiophosphorus - agent for satisfactory treatment of polycythemia and its associated manifestations; report of case of polycythemia secondary possible to Banti's syndrome  
*Ann. Int. Med.*, 19: 587-601
- P 110 Erf, L. A., Lawrence, J. H. Clinical studies with aid of radioactive phosphorus; I. Absorption and distribution of radiophosphorus in blood and its excretion by normal individuals and patients with leukemia. *J. Clin. Invest.* 20:567-75, 1941
- P 111 Erf, L.A., Lawrence, J. H. Clinical studies with the aid of radiophosphorus; III. The absorption and distribution of radiophosphorus in blood of, its excretion by, and its therapeutic effect on, patients with polycythemia. *Ann. Int. Med.* 15:276-90, 1941
- P 112 Erf, L. A., Lawrence, J. H. Phosphorus metabolism in neoplastic tissue. *Proc. Soc. Exp. Biol. and Med.* 46:694-5, 1941
- P 113 Erf, L. A.1 Tuttle, L. W. Phosphorus metabolism of blood of patients with leukemia and polycythemia. *Am. J. M. Sc.* 203:83-7 1942
- P 114 Erf, L.A., Tuttle, L. W.1 Lawrence, J. H. Clinical studies with the aid of radiophosphorus; IV. The retention in blood, the excretion and the therapeutic effect of radiophosphorus on patients with leukemia. *Ann. Int. Med.* 15:487-543, 1941
- P 115 Erf, L. A., Tuttle, L. W., Scott, K. G. Retention of orally administered radiophosphorus by mice. *Proc. Soc. Exp. Biol. and Med.* 45:652-7, 1941
- P 116 Euler, H. v., Ahlstrom, L. and Hogberg, B. Einwirkung von "ontgenstrahlen auf Hefen und Hefenbestandteile. *Arkiv for*

- P 117 Euler, H., Euler, U. S. and Hevesy, G. The effect of excitation on nerve permeability. *Acta Physiologica Scandinavica* 12:261-267, 1946
- P 118 Euler, H. v. and Hevesy, G. v. Wirkung der Rontgenstrahlen auf den umsatz der nukleinsäure im Jensen-Sarkom. *Det Kgl. Danske Videnskabernes Selskab Biologiske Meddelelser*, 17 (No. 8), 1942.
- P 119 Euler, H. and Hevesy, G. Wirkung der Rontgenstrahlen auf den Umsatz der Nukleinsäure im Jensen-Sarkom. *Arkiv for Kemi, Mineralogi Och Geologi* 17A (No. 30): 1-60, 1943.
- P 120 Falkenheim, M., Hodge, H. C. Phosphate desorption from powdered bone as shown by the radioactive isotope. *J. Dental Res.* 24: 195, 1945
- P 121 Fishler, M. C. The site of origin of plasma phospholipids. Thesis Univ. of Cal. June, 1943
- P 122 Fishler, M. C., Entenman, C., Montgomery, M. L., Chaikoff, I. L. The formation of phospholipid by the hepatectomized dog as measured with radioactive phosphorus; I The site of formation of plasma phospholipids. *J. Biol. Chem.* 150:47-55, 1943
- P 123 Fishler, M. C., Taurog, A., Perlman, I., Chaikoff, I. L. The synthesis and breakdown of liver phospholipid in vitro with radioactive phosphorus as indicator. *J. Biol. Chem.* 141:809-18, 1941
- P 124 Fitz-Hugh, T., Jr. Hodes, P. J. Clinical experience with radio-phosphorus in the treatment of certain blood dyscrasias. *Am. J. M. Sc.* 204-662-5, 1942



- P 125 Flock, E. V., Bollman, J. L. Adenosine triphosphate in muscles of rats studied with radioactive phosphorus. J. Biol. Chem. 152:371-83, 1944
- P 126 Flock, E. V., Bollman, J. L. The effect of diethylstilbesterol on the plasma phospholipids of the cock (Gallus Domesticus) J. Biol. Chem. 144:571-577, 1942
- P 127 Flock, E. V., Bollman, J. L. Phospholipid turnover following administration of diethylstilbestrol to cocks. J. Biol. Chem. 156:151-160, 1944
- P 128 Friedlander, H. D., Chaikoff, I. L., Entenman, C. The effect of ingested choline on the turnover of plasma phospholipids. J. Biol. Chem. 158:231-8, 1945
- P 129 Friedlander, H. D., Perlman, I., Chaikoff, I. L. Effects of denervation on phospholipid activity of skeletal muscle as measured with radioactive phos. Am. J. Physiol. 132:24-31, 1941
- P 130 Fries, Bernard A. The lipid metabolism of the brain. Thesis, Univ. of Cal., Graduate Div., 1941
- P 131 Fries, B. A., Chaikoff, I. L. Factors influencing recovery of injected labeled phosphorus in various organs of the rat. J. Biol. Chem. 141:469-78, 1941
- P 132 Fries, B. A., Chaikoff, I. L. Phosphorus metabolism of brain as measured with radioactive phosphorus. J. Biol. Chem. 141:479-85, 1941
- P 133 Fries, B. A., Changus, G. W. and Chaikoff, I. L. Radioactive phosphorus as an indicator of phospholipid metabolism. IX. The influence of age on the phospholipid metabolism of various

- P 134 parts of the central nervous system of the rat. The comparative phospholipid activity of various parts of the central nervous system of the rat. J. Biol. Chem. 132:23-34, 1940
- P 135 Fries, B. A., Ruben, S., Perlman, I., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; II. Role of stomach, small intestine, and large intestine in phospholipid metabolism in presence and absence of ingested fat. J. Biol. Chem. 123:587-93, 1938
- P 136 Fries, B. A., Schachner, H., Chaikoff, I. L. In vitro formation of phospholipid by brain and nerve with radioactive phosphorus as indicator. J. Biol. Chem. 144:59-66, 1942
- P 137 Furchgott, R. F., Shorr, E. Phosphate exchange in resting cardiac muscle as indicated by radioactivity studies. IV. J. Biol. Chem. 151:65-86, 1943
- P 138 Furth, J. Recent experimental studies on leukemia. Physiol. Reviews 26:47-76, 1946
- P 139 Gaunt, W. E., Griffith, H. D., Irving, J. T. Assimilation of radioactive phosphorus following phosphorus deficiency in rats. J. Physiol. 100:372-84, 1942
- P 140 Govaerts, J. Concentration of radiophosphorus  $^{32}\text{P}$  by means of an electrical field. J. Chim. Phys. 36:130, Bull. Soc. Roy. Sci. Liege, Nos. 1, 2
- P 141 Govaerts, J. A photographic method of studying beta ray absorption by  $^{32}\text{P}$ . Nature, 145:624, 1940
- P 142 Graff, W. S., Scott, K. G. and Lawrence, J. L. The histologic effects of radiophosphorus on normal and lymphomatous mice. Am. J. of Roentg. and Radium Therapy 55:44-54, 1946



- P 143 Greenberg, D. M., Aird, R. B., Boelter, M. D., Campbell, W. W. Cohn, W. E., Murayama, M. M. A study with radioactive isotopes of the permeability of the blood-cerebrospinal fluid barrier to ions. *Am. J. Physiol.* 140:47-64, 1943
- P 144 Greenberg, D. M. and Mohamed, M. S. Effect of lowered blood supply and of glucose-1-phosphate on healing of bone fractures. *Proc. Soc. Exper. Biol. & Med.* 57:203-5, 1944
- P 145 Grodzenskiĭ, D. E. Il'ina, L. I. Application of radiophosphorus in biochemical study. *Bull. Acad. Sci. USSR Ser. phys.* 5:604, 1944
- P 146 Grodzenskii, D., Il'ina, L. I. Study of phosphorus metabolism in physiologic and pathologic conditions by means of radioactive phosphorus; technic of experiments and distribution of radioactive phosphorus in various organs of the rats. *Fiziol. Zhur.* 29:341-4, 1940
- P 147 Gunther, L., Cohn, E. T., Cohn, W. E., Greenberg, D. M. Metabolism of bone salts in resistant rickets. Report of a case, with balance and radioactive tracer studies. *Am. J. Diseases of Children.* 66:517-27, 1943
- P 148 Gustafson, F. G. Upward transport of minerals through the phloem of stems. *Science.* 90:306-307, 1939
- P 149 Gustafson, F. G. and Darken, M. Further evidence for the upward transport of minerals through the phloem of stems. *Am. J. of Bot.* 24:615-621, 1937
- P 150 Hahn and Hevesy, The formation of phosphatides in the brain tissue of adult animals. *Skand. Arch. f.* 77:148-157, 1937

- P 151 Hahn, L., Hevesy, G. Formation of phosphatides in blood.  
Compt. rend. trav. lab. Carlsberg. Ser. chim. 22:188-92
- P 152 Hahn, L., Hevesy, G. XLVI Formation of phosphatides in  
liver perfusion experiments. Biochem. J. 32:342-344, 1938
- P 153 Hahn, L. and Hevesy, G. Interaction between the phosphatides  
of the plasma and the corpuscles. Nature, 144:72- ,1939
- P 154 Hahn, L., Hevesy, G. Phosphatide exchange between plasma and  
organs. Nature 144:204, 1939
- P 155 Hahn, L., Hevesy, G. Origin of egg lecithen. Nature 140:1060,  
1938
- P 156 Hahn, L., Hevesy, G. Transaction between the phosphatides of  
the plasma and the corpuscles. Nature 144:72, 1939
- P 157 Hahn, L., Hevesy, G. Turnover rate of nucleic acid. Nature,  
145:549-50, 1940
- P 158 Hahn, L. and Hevesy, G. Rate of penetration of ions through  
the capillary wall. Acta Physiologica Scandinavica. 1:347-  
361, 1941
- P 159 Hahn, L., Hevesy, G. Rate of penetration of ions into erythro-  
cytes. Acta Physiol. Scand. 3:193-223, 1940
- P 160 Hahn, L. A., Hevesy, G., Lundsgaard, E. Circulation of phos-  
phorus in body revealed by application of radioactive phos-  
phorus as indicator. Biochem. J. 31:1705-9, 1937
- P 161 Hahn, P. F., Donald, W. D., Grier, R. C., Jr. Physiological  
bilaterality of portal circulation; streamline flow of blood  
into liver as shown by radioactive phosphorus. Am. J.  
Physiol. 143:105-7, 1945



- P 162 Hall, B. E., Hargraves, M. M., Watkins, C. H. Treatment of polycythemia vera with radioactive phosphorus. Proc. Am. Fed. Clin. Res. 1:25, 1944
- P 163 Hall, B. E., Watkins, C. H., Hargraves, M. M., Giffin, H. Z. Radioactive phosphorus in the treatment of polycythemia vera; results and hematologic complications. Proc. Am. Fed. Clin. Res. 1:51-2, 1945, Am. J. Med. Sci. 209:712-7
- P 164 Hamilton, J. G. The use of radioactive tracers in biology and medicine. Radiology 39:541-72, 1942
- P 165 Hamilton, J. G., Lawrence, J. H. Recent clinical developments in the therapeutic application of radiophosphorus and radioiodine J. Clin. Invest. 21:624, 1942
- P 166 Hammarsten, E. and Hevesy, G. Rate of renewal of ribo and desoxy-ribo nucleic acid. Acta Physiologica Scandinavica 11:335-343, 1946
- P 167 Haven, F. L. Phospholipid metabolism studies using radioactive phosphorus. J. App. Physics 12:320, 1941
- P 168 Haven, F. L. The phospholipid metabolism of tumors. J. Biol. Chem. 118:111-21, 1937
- P 169 Haven, F. L., Bale, W. F. The fate of phospholipid injected intravenously into the rat. J. Biol. Chem. 129:23-32, 1939
- P 170 Haven, F. L., Bale, W. F., LeFevre, M. L. Comparative distribution in the white rat of radioactive phosphorus fed as sodium phosphate and injected as phospholipid. J. Biol. Chem. 123: , 1938

- P 171 Haven, F. L., Levy, S. R. The occurrence and rate of turnover of tumor sphingomyelin. *J. Biol. Chem.* 141:417-25, 1941
- P 172 Haven, F. L., Levy, S. R. Rate of turnover of lecithins and cephalins of carcinosarcoma 256 as measured by radioactive phosphorus. *J. Nat. Cancer Inst.* 1:205-9, 1940
- P 173 Hempelmann, L. H., Jr. Reinhard, E. H., Moore, C. V., Bierbaum, O. S., and Moore, S. Hematologic complications of therapy with radioactive phosphorus. *J. Lab. & Clin. Med.* 29:1020-41, 1944
- P 174 Hempelmann, L. A., Jr. and others Hematologic complications of therapy with radioactive phos. *J.A.M.A.* 124:735, 1944
- P 175 Henderson, W. J., Jones, U. S. The use of radioactive elements for soil and fertilizer studies. *Soil Sci.* 51:283-388, 1941
- P 176 Hevesy, G. Radioactive elements as indicators in Chem. and Biol. research. *Paneth Sci. Prog.* 32:38, 1937
- P 177 Hevesy, G. Celebration of the second centenary of the birth of Luigi Galvani. Radioactive phosphorus as an indicator in biology. *Nuovo Cimento* 15:279-312, 1938
- P 178 Hevesy, G. Interaction between the phosphorus atoms of the wheat seedling and the nutrient solution. *Arkiv for Botanik* Band 33A. No. 2, 1946
- P 179 Hevesy, G. Rate of renewal of the fish skeleton. *Acta Physiologica Scandinavica* 9:234-247, 1945
- P 180 Hevesy, G. and others Red corpuscle content of circulating blood determined by labelling erythrocytes with radio-phosphorus. *Acta med. Scand.* 116:561-76, 1945



- P 181 Hevesy, G., Aten, A. H. W. Interaction of plasma phosphate with the phosphorus compounds present in the corpuscles. Kgl. Danske. Videnskab. Selskab Biol. Medd. 14:5, 1939
- P 182 Hevesy, G., Baranowski, T., Guthke, J., Ostern, P. and Parnas, J. K. Badania Nad Glikoliza. Nowa metoda z zastosowaniem fosforu promieniotwórczego. Odbitka ze Sprawozdan T-Wa Naukowego we Lwowie rok XVIII zeszyt 1, 1938
- P 183 Hevesy, G., Baranowski, T., Guthke, A. J., Ostern, P., Parnas, J. K. Untersuchungen über die Phosphorübertragungen in der Glykolyse und Glykogenolyse. Acta Biol. Exp. (Warsaw) 12:3409, 1938
- P 184 Hevesy, G. v., Euler, H. v. The permeability of the cell wall of a sarcoma to phosphate and the velocity of neoformation of phosphorus-containing compounds in the sarcoma cells. Arkiv Kemi, Mineral. Geol. A15, No. 15, 1-17, Chem. Zentr. II:905-6, 1942
- P 185 Hevesy, G., Hahn, L. Origin of P compounds in hens' eggs. Det. Kgl. Danske Viden. Selskab. Biol. Medd. 14:2, 1938
- P 186 Hevesy, G., Hahn, L. Rate of penetration of phosphatides through the capillary wall. Kgl. Danske Videnskab. Selsk. Biol. Medd. 15:6, 1940
- P 187 Hevesy, G., Hahn, L. Rate of renewal of the acid-soluble organic phosphorus compounds in the organs and the blood of the rabbit. With a note on the duration of life of the red blood corpuscles. Kgl. Danske Videnskab. Selskab Biol. Medd. 15:36, 1940
- P 188 Hevesy, G., Hahn, L. Turnover of lecithin, cephalin, and sphingomyelin. Kgl. Danske Videnskab. Selskab Biol. Medd. 15:60, 1940

- P 189 Hevesy, G., Hahn, L., Rebbe, O. Circulation of phosphorus in the frog. With a note on the circulation of potassium. K. Danske Videnskab. Selskab Biol. Medd. 16:1-33, 1941
- P 190 Hevesy, G., Hahn, L., Rebbe, O. Excretion of phosphorus. Kgl. Danske. Videnskab. Selskab. Biol. Medd. 14:3, 1939
- P 191 Hevesy, G., Holst, J. J., Krogh, A. Investigations on the exchange of phosphorus in teeth using radioactive phosphorus as indicator. Kgl. Danske Videnskab. Selskab. Biol. Medd. 13:34, 1937
- P 192 Hevesy, G., Koster, K. H., Sorensen, G., Warburg, E. and Zerahn, K. The red corpuscle content of the circulating blood determined by labelling the erythrocytes with radio-phosphours. Acta Medica Scandinavica. 116: Fasc. V-VI, 1944
- P 193 Hevesy, G., Levi, H. B., Rebbe, O. H. The origin of the phosphorus compounds in the embryo of the chicken. Biochem. J. 32:2147, 1938
- P 194 Hevesy, G., Linderstrom-Lang, K., Olsen, C. Exchange of phosphorus atoms in plants and seeds. Nature 139:149-50, 1937
- P 195 Hevesy, G., Linderstrom-Lang, K., Nielsen, N. Phosphorus exchange in yeast. Nature 140:725
- P 196 Hevesy, G., Lundegaard, E. Lecithinemia following the administration of fat. Nature. 140:275, 1937
- P 197 Hevesy, G. and Ottesen, J. Rate of formation of nucleic acid in the organs of the rat. Acta Physiologica Scandinavica 5: Fasc 2-3, 1943
- P 198 Hevesy, G., Rebbe, O. Rate of penetration of phosphate into muscle cells. Acta Physiol. Scand. 1:171-82, 1940
- P 199 Hevesy, G. C., Smedley-MacLean, I. Synthesis of phospholipin in rats fed on fat-deficient diet. Biochem. J. 34:903-5, 1940



- P 200 Hevesy, G. and Zerahn, K. Determination of the red corpuscle content. *Acta Physiologica Scandinavica*. 4:3-4, 1942
- P 201 Hevesy, G. and Zerahn, K. The effect of roentgen rays and ultraviolet radiation on the permeability of yeast. XXVII: 157-158, 1946
- P 202 Hoagland, D. R., Broyer, T. C., Stout, P. R. Upward movement of salt in the plant with special reference to metabolic activities of roots. *Science* 91:454, 1940
- P 203 Hodge, Harold C., Falkenheim, Marlene The absorption of phosphates by enamel, dentine, and bone II. The adsorption rates from concentrated solution. *J. Biol. Chem.* 160:637-8, 1945
- P 204 Hodge, H. C., Koss, W. F., Ginn, J. T., Falkenheim, M., Gavett, E., Fowler, R. C., Thomas, I., Bonner, J. F., Dessauer, G. The nature of the insoluble sodium of bone. The adsorption of sodium at 40° by bone, dentine, enamel & hydroxyapatite as shown by the radioactive isotope. *J. Biol. Chem.* 148:321-31, 1943
- P 205 Hodge, H. C. and Sterner, J. H. The skin absorption of triorthocresyl phosphate as shown by radioactive phosphorus. *J. of Phar. and Exper. Therapeutics* 79:225-234, 1943
- P 206 Hodge, H. C., Van Huysen, G., Bonner, J. F. and Van Voorhis, S. N. The adsorption of phosphates at forty degrees by enamel, dentin, bone, and hydroxyapatite as shown by the radioactive isotope. *J. Biol. Chem.* 138:451-457, 1941
- P 207 Hoster, H. A., Doan, C. A. Studies in Hodgkin's syndrome; IV The therapeutic use of radioactive phosphorus. *J. Lab & Clin. Med.* 30:678-683, 1945

- P 208 Hunter, F. E. Entrance of radioactive phos. into sphingomyelin of various tissues of cat. Proc. Soc. Exper. Biol. & Med. 46:2812, 1941
- P 209 Hunter, F. E., Levy, S. R. Occurrence & rate of turnover of sphingomyelin in tissues of normal and tumor-bearing rats. J. Biol. Chem. 146:577-81, 1943
- P 210 Jacobson, L. O., Spurr, C. L., Smith, T. R. and Dick, G. F. Radioactive phosphorus ( $P^{32}$ ) and alkylamines (nitrogen mustards) in the treatment of neoplastic and allied diseases of the hemopoietic system. The medical clinics of North America. Jan. 1947 Chicago Number, 1947
- P 211 Johansson, E. G., Falkenheim, M., Hodge, H. C. The adsorption of phosphates by enamel, dentin & bone. I. Adsorption time studied by means of the radioactive isotope. J. Biol. Chem. 159:129-134, 1945
- P 212 Jones, Hardin Blair Studies of phosphorus metabolism in normal and neoplastic tissues of the mouse as indicated by radioactive phosphorus. Thesis, Univ. of Cal. Graduate Div. 1944
- P 213 Jones, H. B., Chaikoff, I. L., and Lawrence, J. H. Radioactive phosphorus as an indicator of phospholipid metabolism. X. The phospholipid turnover of fraternal tumors. J. Biol. Chem. 133:319-327, 1940
- P 214 Jones, H. B., Chaikoff, I. L., and Lawrence, J. H. Phosphorus metabolism of neoplastic tissues (Mammary carcinoma, lymphoma, lymphosarcoma) as indicated by radioactive phosphorus. Am. J. Cancer XL:243-250, 1940



- P 215 Jones, H. B., Chaikoff, I. L. and Lawrence, J. H. Phosphorus metabolism of the soft tissues of the normal mouse as indicated by radioactive phosphorus. Phosphorus metabolism of neoplastic tissues (mammary carcinoma, lymphoma, lymphosarcoma) as indicated by radioactive phosphorus. Am. J. of Cancer. XL:235-250, 1940
- P 216 Jones, H. B., Chaikoff, I. L., Lawrence, J. H. Radioactive phosphorus as an indicator of phospholipid metabolism; VI The phospholipid metabolism of neoplastic tissues (mammary carcinoma, lymphoma, lymphosarcoma, sarcoma 180). J. Biol. Chem. 128:631-44, 1939
- P 217 Jones, H. B., Wrobel, G. J., Lyons, W. R. A method of distributing beta-radiation to the reticulo-endothelial system and adjacent tissues. J. Clin. Inv. 23:783-88, 1944
- P 218 Kalckar, H. M. Rejuvenation of phosphate-adenine nucleotides I. enzymatic methods for separation of phosphate groups in polyphosphorylated nucleotides. J. Biol. Chem. 154:267-73, 1944
- P 219 Kalckar, H. M., Dehlinger, J., Mehler, A. Rejuvenation of phosphate in adenine nucleotides II. The rate of rejuvenation of labile phosphate compounds in muscle and liver. J. Biol. Chem. 154:275-91, 1944
- P 220 Kaplan, N., Greenberg, D. M. Observations with  $P^{32}$  of the changes in the acid-soluble phosphates in the liver coincident to alterations in carbohydrate metabolism. J. Biol. Chem. 150:479-80, 1944
- P 221 Kaplan, N. O., Greenberg, D. M. Radioactive phosphate as an indicator of the relationship between the phosphate changes of

blood, muscle, and liver, following the administering of insulin.  
Am. J. Physiol. 140:598-602, 1944

- P 222 Kaplan, N. O., Greenberg, D. M. Studied with radioactive phos. of changes in the acid-soluble phosphates in the liver coincident to alterations in carbohydrate metabolism; I. separation and nature of the organic acid-soluble phosphates of liver. J. Biol. Chem. 156:511-24, 1945
- P 223 Kaplan, N. O., Greenberg, D. M. Studied with radioactive phos. of the changes in the acid-soluble phosphates in the liver coincident to alterations in carbohydrate metabolism; II. The effect of glucose, insulin, and of certain metabolic inhibitors. J. Biol. Chem. 156:525-42, 1945
- P 224 Kaplan, N. O., Greenberg, D. M. Studies with radioactive phos. of the changes in the acid-soluble phosphates in the liver coincident to alterations in carbohydrate metabolism; III. The effect of fasting and of high fat, high carbohydrate, and high protein diets. J. Biol. Chem. 156:543-51, 1945
- P 225 Kaplan, N. O., Memlsdorff, Ilsa, Dodge, Ethel, Aerobic phosphorylations in tissue slices. J. Biol. Chem. 160:631-2, 1946
- P 226 Kenney, J. M. Radioactive phos. as a therapeutic agent in malignant neoplastic disease. Cancer Res. 2:130-45, 1942
- P 227 Kenney, J. M., Craver, L. F. Further experiences in treatment of lymphosarcoma with radioactive phos. Radiol. 39:598-607, 1942
- P 228 Kenney, J. M., Marinelli, L. D., Craver, L. F. The treatment of lymphosarcoma with radioactive phos; a preliminary report. Am. J. Roentg. 47:217-26, 1942



- P 229 Kenney, J. M., Marinelli, L. D., Woodard, H. Q. Tracer studies with radioactive phos. in malignant neoplastic disease. Radiol. 37:683-87, 1941
- P 230 Kinsell, L. W. Uptake of radioactive phos. ( $P^{32}$ ) in rapidly regenerating tissue, and in normal adult tissue, in human subject. Proc. Am. Fed. Clin. Res. 1:51, 1944
- P 231 Kjerulf-Jensen, K. Excretion of phos. by bowel. Acta physiol. Scandinav. 3:1-27, 1941
- P 232 Kinsey, V. E. and others Sodium, Chloride and phosphorus movement and the eye. Archives of Ophthalmology 27:1126-1131, 1942
- P 233 Koepsell, H. J., Johnson, M. J., Meek, J. S. Role of phosphate in pyruvic acid dissimilation by cell-free extracts of clostridium butylicum. J. Biol. Chem. 154:535, 1944
- P 234 Kohman, T. P., Rusch, H. P. Relative metabolic activities of normal and tumorous liver nucleoproteins indicated by radiophosphorus. Proc. Soc. Exper. Biol. & Med. 46:403-4, 1941
- P 235 Korzybski, T., Parnas, J. K. The conversion of adenosine triphosphate in living animals. Acta Biol. Exptl. (Warsaw) 13:157-65, 1939
- P 236 Lawrence, J. H., Observations on the nature & treatment of leukemia and allied diseases (Edwin R. Kretschmer Memorial Lecture) Proc. Inst. Med. Chicago 14:30-49, 1942
- P 237 Lawrence, J. H., Erf, L. A., Tuttle, L. W. Intracellular irradiation. J. App. Physics 12:333, 1941
- P 238 Lawrence, J. H., Scott, K. G. Comparative metabolism of phosphorus in normal and lymphomatous animals. Proc. Soc. Exper. Biol. & Med. 40:694-96, 1939

- P 239 Lawrence, J. H., Scott, K. H., Tuttle, L. W. Studies on leukemia with aid of radioactive phosphorus. *Internat. Clin.* 3:33-58, 1939
- P 240 Lawrence, J. H., Tuttle, L. W., Scott, K. G., Connor, C. L. Studies of neoplasms with aid of radioactive phosphorus. I. Total phosphorus metabolism of normal and leukemic mice. *J. Clin. Inv.* 19:267-71, 1940
- P 241 Levi, Hilde The action of honey bee-venom on red corpuscles especially on their ionic permeability. *Arkiv For Kemi, Mineralogi Och Geologi* Band 21A No. 5, 1945
- P 242 Lindgren, E. Versuche mit radioaktiven isotopen bei leukamiebehandlung *Acta. Radiol.* 25:614-24, 1944
- P 243 Lindsay, E., Craig, R. Distribution of radiophosphorus. in wax moth, mealworm, cockroach and firebrat. *Ann. Entomol. Soc. Am.* 35:50-6, 1942
- P 244 Lipmann, Fritz, Tuttle, L. Constance On the condensation of acetyl phosphate with formate or carbon dioxide in bacterial extracts. *J. Biol. Chem.* 158:505
- P 245 Lorenz, F. W., Chaikoff, I. L., Entenman, E. Liver lipides of the laying and non-laying bird. *J. Biol. Chem.* 123:577-85, 1938
- P 246 Lorenz, F. W., Perlman, I., Chaikoff, I. L. Phosphorus deposition in the egg as measured with radioactive phosphorus. *Am. J. Physiol.* 138:318-327, 1943
- P 247 Lovera, Giuseppe; Tappi, G. Preparation and testing of radioactive phosphorus for biological use. *Ricerca sci.* 10:177, 1939
- P 248 Low-Beer, B. V. A. External therapeutic use of radioactive phosphorus. I. Erythema Studies. *Radiology* 47:213-222, 1946



- P 249 Low-Beer, B. V. A. Surface measurements of radioactive phosphorus in breast tumors as a possible diagnostic method. *Science* 104: 399, 1946
- P 250 Low-Beer, B. V. A., Bell, H. G., McCorkle, H. J. and Stone, R. S. (assisted by Steinbach, H. L. and Hill, W. B.) Measurement of radioactive phosphorus in breast tumors in situ; a possible diagnostic procedure. *Radiology* 47:492-493, 1946
- P 251 Low-Beer, B. V. A., Lawrence, J. H. and Stone, R. S. The therapeutic use of artificially produced radioactive substances (Radiophosphorus, radiostrontium, radioiodine, with special reference to leukemia and allied diseases) *Radiology* 39:573-97, 1942
- P 252 Low-Beer, B. V. A., Treadwell, A. deG. Clinical studies with aid of radioactive phosphorus; early effects of small amounts of radioactive phosphorus on blood cell levels, uptake and excretion. *J. Lab. & Clin. Med.* 27:1294-1305, 1942
- P 253 Mallet, L., LeCamus, H. Le radio-phosphore et son utilisation biologique. *J. de radiol. et d'electrol.* 25:168-71, 1942-43
- P 254 Manery, J. F., Bale, W. F. The penetration of radioactive sodium and phosphorus into extra- and intra-cellular phases of tissues. *Am. J. Physiol.* 132:215-31, 1941
- P 255 Manly, M. L., Bale, W. F. Metabolism of inorganic phosphorus of rat bones and teeth as indicated by radioactive isotope. *J. Biol. Chem.* 129:125-134, 1939
- P 256 Manly, R. S., Hodge, H. C., Manly, M. L. Relation of phosphorus turnover of blood to mineral metabolism of calcified tissues as shown by radioactive phosphorus. *J. Biol. Chem.* 134:293-299, 1940

- P 257 Manly, M. L., Hodge, H. C., VanVoorhis, S. N. Distribution of ingested phosphorus in bone and teeth of a dog, shown by radioactive isotope. *Proc. Soc. Exper. Biol. & Med.* 45:70-2, 1940
- P 258 Manly, M. L., Levy, S. R. Adsorption studies on enamel, dentine and bone. *J. Am. Chem. Soc.* 61:2588-2590, 1939
- P 259 Manly, M. L., Levy, S. R. Effect of pregnancy on the phosphorus turnover of the skeleton of rats maintained on normal and rachitogenic diets. *J. Biol. Chem.* 139:35-41, 1941
- P 260 Marinelli, L. D., Goldschmidt, B. Concentration of  $P^{32}$  in some superficial tissues of living patients. *Radiol.* 39:454-63, 1942
- P 261 Marinelli, L. D., Kenney, J. M. The absorption of radiophos in irradiated and non-irradiated mice. *Radiol.* 37:691-7, 1941
- P 262 Marshak, A.,  $P^{32}$  uptake by nuclei. *J. Gen. Physiol.* 25:275-91, 1941
- P 263 Marshak, A. Uptake of radioactive phosphorus by nuclei of liver and tumors. *Science* 92:460-1
- P 264 Marshak, A., Walker, A. C. Transfer of  $P^{32}$  from intravenous chromatin to hepatic nuclei. *Am. J. Physiol.* 143:235-37, 1945
- P 265 McCoy, O. R., Downing, V., VanVoorhis, S. The penetration of radioactive phosphorus into encysted trichinella larvae. *J. Parasitol.* 27:53-8, 1941
- P 266 McDonald, E. Annual report of the Biochemical Research Foundation of the Franklin Institute. Radioactivity and Biochemistry. J. Franklin Institute 241:23-29, 1946
- P 267 Meyerhof, O. Use of radioactive phosphorus in the study of glycolysis and fermentation. *Bull. soc. chim. biol.* 21:1094-1101, 1939



- P 268 Meyerhof, O., Ohlmeyer, P., Gentner, W., Maier-Leibnitz, H. Studies on the intermediate reactions of glucolysis with the aid of radioactive phosphorus. *Biochem. Z.* 298:396-411, 1938
- P 269 Morgareidge, K., Manly, M. L. Simultaneous appearance of a positive line test and radioactive phosphate deposition in the rachitic rat metaphysis. *J. Nutr.* 18:411-21
- P 270 Muir, Robert M. Effect of radiation from radioactive isotopes on the protoplasm of *Spirogyra*. *J. Cellular Comp. Physiol.* 19:244-7, 1942
- P 271 Mullins, L. J. The permeability of yeast cells to radiophosphate. *Biol. Bull.* 83:326, 1942
- P 272 Myers, W. G. Some applications of atomic energy to diagnosis and therapy. *Ohio J. Sci.* 46:197-199, 1946
- P 273 Newell, R. R., Falconer, E. H., Hill, H. P., Lawrence, J. H., Wood, D. A., and Wyckoff, H. Panel discussion on the leukemias and lymphoblastomas. *Radiology* 39:298-305, 1942
- P 274 Nielson, P. E. Study with radioactive phosphorus of permeability of rat placenta to phospholipid. *Am. J. Physiol.* 135:670-675, 1942
- P 275 Nylin, G. Blood volume determinations with radioactive phosphorus. *Brit. Heart J.* 7:81-84, 1945
- P 276 Nylin, G. The dilution curve of activity in arterial blood after intravenous injection of labeled corpuscles. *Am. Heart J.* 30:1-11, 1945
- P 277 Nylin, G., Malm, M. Ueber die Konzentration von mit radioaktiven phosphor markierten Erythrocyten im Arterienblut nach der intravenösen injektion solcher Blutkörperchen. (Vorläufige Mitteilung). *Cardiologia.* 7:153-162, 1943

- P 278 Nylin, G., Malm, M. Concentration of red blood corpuscles containing labeled phosphorus compounds in the arterial blood after the intravenous injection; preliminary report. Am. J. M. Sc. 207:743-49, 1944
- P 279 Osgood, E. E., Aebersold, P. C., Erf, L. A., Packham, E. A. Studies of the effects of million volt roentgen rays, 200 kilovolt roentgen rays, radioactive phosphorus, and neutron rays by the marrow culture technique. Am. J. M. Sc. 204:372-81, 1942
- P 280 Overstreet, R., Jacobson, L. The absorption by roots of rubidium and phosphate ions at extremely small concentrations as revealed by experiments with  $\text{Rb}^{86}$  and  $\text{P}^{32}$  prepared without inert carrier. Am. J. Botany 33; 107-12, 1946
- P 281 Patterson, J. M., Keevil, N. B., McHenry, E. W. Choline and the prevention of hemorrhagic kidneys in the rat; II phospholipid turnover determined with radioactive phosphorus. J. Biol. Chem. 153:489-93, 1944
- P 282 Perlman, Isadore Studies on the phospholipid metabolism of the liver using radioactive phosphorus as an indicator. Thesis, Univ. of Cal., Graduate Div. 1940
- P 283 Perlman, I. and Chaikoff, I. L. Radioactive phosphorus as an indicator of phospholipid metabolism. V. On the mechanism of the action of choline upon the liver of the fat-fed rat. J. Biol. Chem. 127:211-220, 1939
- P 284 Perlman, I., Chaikoff, I. L. The phospholipid activity of the liver as measured with radioactive phosphorus. J. App. Physics 12:319, 1941



- P 285 Perlman, I., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; VIII. Influence of betaine on phospholipid activity of liver. J. Biol. Chem. 130:593-600, 1939
- P 286 Perlman, I., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; influence of cholesterol upon phospholipid turnover in liver. J. Biol. Chem. 128:735-43, 1939
- P 287 Perlman, I., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; V. On mechanism of action of choline upon the liver of fat-fed rat. J. Biol. 127:211-20, 1939
- P 288 Perlman, I., Ruben, S., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; I. Rate of formation and destruction of phospholipids in fasting rat. J. Biol. Chem. 122:169-82, 1937
- P 289 Perlman, I., Stillman, N., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; XII Further observations on effects of amino acids on phospholipid activity of liver. J. Biol. Chem. 135:359-64, 1940
- P 290 Perlman, I., Stillman, N., Chaikoff, I. L. Radioactive phosphorus as indicator of phospholipid metabolism; XI. Influence of methionine, cystine, and cysteine upon phospholipid turnover in liver. J. Biol. Chem. 133:651-9, 1940
- P 291 Perrier, C., Artom, C., Santangelo, M., Sarzana, G., Segre, E. Phospholipide synthesis during fat absorption. Nature. 139:1105-6, 1937
- P 292 Perrier, C., Segre, E. Ricerca sullo scambio del fosforo in taluni composti. Ricerca sci. 9:638:11-12, 1938

- P 293 Rapoport, S. and Guest, G. M. Distribution of acid-soluble phosphorus in the blood cells of various vertebrates. J. Biol. Chem. 138:269-282, 1941
- P 294 Rapoport, S., Leva, E. and Guest, G. M. Phosphorus exchange in phytate, lipids, and nucleoproteins in the erythrocytes of geese. J. Biol. Chem. 139:633,639, 1941
- P 295 Rapoport, S., Nelson, N., Guest, G. M., Mirsky, I. A. The turnover of acid-soluble phosphorus in the kidney of rats. Science 93: 88-89, 1941
- P 296 Reed, Carlos I. Metabolism of calcium and phosphorus. Rev. argentino-norteamer, cienc. med. (Buenos Aires) 1:695-705, 1946
- P 297 Reinhard, E. H., Moore, C. V., Bierbaum, O. S., Kamen, M. Radioactive phosphorus as a therapeutic agent. A review of the literature and analysis of the results of treatment of 155 pts. with various blood dyscrasias, lymphomas, and other malignant neoplastic diseases. J. Lab. & Clin. Med. 31:107-218, 1946
- P 298 Reinhardt, W. O., Fishler, M. C., Chaikoff, I. L. The circulation of plasma phospholipides; their transport to thoracic-duct lymph. J. Biol. Chem. 152:79-82, 1944
- P 299 Rhoads, C. P. Medical uses of atomic energy. U. S. Atomic Energy Commission, Vol. V. 1946
- P 300 Riley, R. F. Metabolism of phosphoryl choline. I. Synthesis of Ca phosphoryl choline chloride containing radioactive isotope,  $p^{32}$ . J. Am. Chem. Soc. 66:512-13, 1944
- P 301 Riley, R. F. Metabolism of phosphorylcholine II. Partition of phosphoryl choline P between blood phosphate fractions. J. Biol. Chem. 153:537-41, 1944



- P 302 Riley, R. F. Metabolism of phosphorylcholine III. Partition of phosphorylcholine P between tissues. J. Biol. Chem. 153:541-4, 1944
- P 303 Riley, R. F. Metabolism of phosphorylcholine IV. Distribution of phosphorylcholine P in tissue lipides. J. Biol. Chem. 153:544-9, 1944
- P 304 Riley, R. F., McCleary, B., Johnson, R. E. Denervation atrophy of bone and muscle. An examination of the effect of choline and some further observations on the metabolism of phosphorylcholine and deposition of P<sup>32</sup> in bone. Am. J. Physiol. 143:677-686, 1945
- P 305 Robinson, A., Perlman, I., Ruben, S., Chaikoff, I. L. Formation of radio-phospholipid by isolated tissues of the rat. Nature. 141: 119, 1938
- P 306 Ross, O. A. Use of radioactive phosphorus as tracer in hemolytic streptococci; detection of assimilated radioactivity in treated fractions of sonically vibrated organisms. J. Immunol. 44:329-36, 1942
- P 307 Sacks, J. The absence of phosphate transfer in oxidative muscular contraction. Am. J. Physiol. 140:316-20, 1943
- P 308 Sacks, J. The effect of insulin on phosphorus turnover in muscle. Am. J. Physiol. 143:157-162, 1945
- P 309 Sacks, J. Radioactive phosphorus studies on hexosemonophosphate metabolism in resting muscle. Am. J. Physiol. 142:145-51, 1944
- P 310 Sacks, J. Radioactive phosphorus as a tracer in anaerobic muscular contraction. Am. J. Physiol. 129:227-33, 1940

- P 311 Sacks, J. Radioactive phosphorus studies on muscle hexosephosphates. Univ. Hosp. Bull., Ann Arbor, 9:33-34, 1943
- P 312 Sacks, J. Radio-phosphorus studies in the chemistry of anaerobic muscular contraction. J. App. Physics 12:320, 1941
- P 313 Sacks, J. Some factors influencing phosphate turnover in muscle. Am. J. Physiol. 142:621-6, 1944
- P 314 Sacks, J. On the mechanism of insulin action; observations with radioactive phosphorus. Science 98:388-89, 1943
- P 315 Sacks, J., Altshuler, C. H. Radioactive phosphorus studies on striated and cardiac muscle metabolism. Am. J. Physiol. 137:750-60, 1942
- P 316 Salter, William T. Tracer substances in nutrition. Chapter 9 of book entitled "Dietotherapy".
- P 317 Saralegui, J. A., Pavlovsky, A. Tratamiento de las leucemias con el fosforo radioactivo. Radiologia 6:88-97, 1943
- P 318 Schachner, Hermann, The formation of phospholipids by surviving brain tissue. Thesis, Univ. of Cal. Graduate Div. 1943
- P 319 Schachner, H., Fries, B. A., Chaikoff, I. L. Effect of hexoses and pentoses on formation in vitro of phospholipid by brain tissue as measured with radioactive phosphorus. J. Biol. Chem. 146:95-103, 1942
- P 320 Scott, K. G. Metabolic studies on leukemic mice with the aid of radioactive phosphorus. Cancer Res. 5:365-367, 1945
- P 321 Scott, K. G., Cook, S. F. Effect of radioactive phosphorus upon blood of growing chicks. Proc. Nat. Acad. Sci. 23:265-72, 1937



- P 322 Scott, K. G., Lawrence, J. H. Effect of radiophos on blood of monkeys. *Proc. Soc. Exper. Biol. & Med.* 48:155-158, 1941
- P 323 Shcherba, S. V. Effect on crops of various forms of phosphate fertilizers applied systematically. *Chemisation Socialistic Agr. (USSR)* 8:26-32, 1939
- P 324 Shimotori, N., Morgan, A. F. Mechanism of vitamin D action in dogs shown by radioactive phosphorus. *J. Biol. Chem.* 147:201-210, 1943
- P 325 Sognnaes, R. F., Volker, J.F. Studies on distribution of radioactive phosphorus in tooth enamel of experimental animals. *Am. J. Physiol.* 113:112-20, 1941
- P 326 Sognnaes, R. F., Volker, J. F. The exchange of radiophosphorus in the various parts of the enamel. *J.Am. Coll. Dentists* 8:57, 1941
- P 327 Stanley, W. M. The preparation and use of tobacco mosaic virus containing radioactive phosphorus. *J. Gen. Physiol.* 25:881-90, 1942
- P 328 Stillman, N., Entenman, C., Anderson, E., Chaikoff, I. L. Phosphorylation of fat in absence of adrenal glands as measured with radioactive phosphorus. *Endocr.* 31:481-5, 1942
- P 329 Stout, P. R. Applications of radioactive K., Rb, Na, P, and Br to studies of the mineral nutrition of higher plants. *J. App. Physics* 12:327, 1941
- P 330 Stout, P. R. & Hoagland, D. R. Upward and lateral movement of salt in certain plants as indicated by radioactive isotopes of potassium, sodium, and phosphorus, absorbed by roots. *Am. J. Botany* 26:320-4, 1939

- P 331 Sugiura, K. The effect of radioactive phosphorus on the viability of mouse sarcoma 180. *Cancer Res.* 2:19-24, 1942
- P 332 Taurog, Alvin Studies in phospholipid formation in vitro in liver and kidney. Thesis, Univ. of Cal., Graduate Div. 1943
- P 333 Taurog, A., Chaikoff, I. L., Perlman, I. The effect of anaerobic conditions and respiratory inhibitors on the in vitro phospholipid formation in liver and kidney with radioactive phosphorus as indicator. *J. Biol. Chem.* 145:281-91, 1942
- P 334 Taurog, A., Entenman, E., Fries, B. A. An adsorption procedure for the separation of choline-containing from noncholine-containing phospholipides of liver. *J. Biol. Chem.* 155:19-25
- P 335 Taurog, A., Entenman, C., Chaikoff, I.L. Choline-containing and non-choline-containing phospholipids of plasma. *J. Biol. Chem.* 156:385-391, 1944
- P 336 Taurog, A., Lorenz, F. W., Entenman, C., Chaikoff, I.L. Effect of diethylstilbestrol on in vitro formation of phospholipids in liver as measured with radioactive phosphorus. *Endocr.* 35:483-487, 1944
- P 337 Taylor, A., Pollack, M.A., Williams, R. J. The determination of blood volume with red blood cells containing radioactive phosphorus ( $P^{32}$ ). *Science* 96:322-23, 1942
- P 338 Tuttle, L. W., Erf, L. A., Lawrence, J. H. Studies on neoplasms with aid of radioactive phosphorus II. Phosphorus metabolism of nucleoprotein phospholipid and acid soluble fractions of normal and leukemic mice. *J. Clin. Inv.* 20:57-61, 1941
- P 339 Tuttle, L. W., Erf, L. A., Lawrence, J. H. Studies on neoplasms with the aid of radioactive phosphorus III. The phosphorus metabo-



- P 340 lism of the phospholipid, acid soluble, and nucleoprotein fractions of various tissues of normal and leukemic mice following the administration of "tracer" and "therapeutic" doses of radiophosphorus. J. Clin. Inv. 20:577-81, 1941
- P 341 Tuttle, L. W., Scott, K. G., Lawrence, J. H. Phosphorus metabolism in leukemic blood. Proc. Soc. Exper. Biol. & Med. 41:20-25, 1939
- P 342 Tuve, M. A. High-energy radiations and their applications. Occas. Publ. Amer. Assoc. Advancement Sci. 4(Suppl. Science) 85:183-195, 1937
- P 343 Tweedy, W. R., Campbell, W. W. The effect of parathyroid extract upon the distribution, retention and excretion of labeled phosphorus. J. Biol. Chem. 154:339-47, 1944
- P 344 Utter, M. F., Krampitz, L. O., Werkman, C. H. Oxidation of acetyl phosphate and other substrates by *Micrococcus lysodeikticus*. Arch. Biochem. 9:285-300, 1946
- P 345 Utter, M. F., Werkman, C. H. Formation and reactions of acetyl phosphate in *Esch. Coli*. Arch. Biochem. 5:413-422, 1944
- P 346 Utter, M. F., Werkman, C. H. Role of phosphate in the anaerobic dissimilation of pyruvic acid. Arch. Biochem. 2:491-492, 1943
- P 347 Volker, J. F. The phosphate metabolism of the erupted tooth as indicated by studies utilizing the radioactive isotope. Tufts Dental Outlook.
- P 348 Volker, J. F., Sognaes, R. F. Distribution of radioactive phosphorus in teeth of experimental animals. J. Dent. Res. 20:471-6, 1941

- P 349 Volker, J. F., Sognnaes, R. F., Bibby, G. B. Observations on the radiophosphorus metabolism of teeth and bones of experimental animals. J. Am. Coll. Dentists 8:56, 1941
- P 350 Warren, Stafford L. Biological damage and precautionary tests. J. App. Physics 12:343, 1941
- P 351 Warren, S. The distribution of doses of radioactive phosphorus in leukemic patients. Cancer Res. 3:334-336, 1943
- P 352 Warren, S. The retention of radioactive phosphorus in leukemic patients. Cancer Res. 3:872-876, 1943
- P 353 Warren, S. The therapeutic use of radioactive phosphorus. Am. J. M. Sc. 209:701-711, 1945
- P 354 Warren, S. The treatment of leukemia by radioactive phosphorus. N. Eng. J. Med. 223:751-754, 1940
- P 355 Warren, S., Cowing, R. F. The retention of radioactive phosphorus when administered in different chemical forms. Cancer Res. 4:113-115, 1944
- P 356 Warren, S., Cowing, R. F. The distribution of doses of radioactive phosphorus in rodents. J. Lab. & Clin. Med. 26:1014-1016, 1941
- P 357 Wassermann, F., Blayney, U. R., Groetzinger, G., DeWitt, T. G. Studies on different pathways of exchange of minerals in teeth with aid of radioactive phosphorus. J. Dent. Res. 20:389-98, 1941
- P 358 Watkins, C. H., Hall, B. E., Hargraves, M. M., Giffin, H. Z. Radioactive phosphorus in the treatment of polycythemia vera; results and hematologic complications. Am. J. Med. Sc. 209:712, 1945
- P 359 Webster, C. Use of radioactive phosphorus in treatment of leukemia. Texas Rep. Biol. & Med. 2:83-88, 1944



- P 360 Weissberger, L. H. The increase in phospholipid and total phosphorus metabolism of the kidney following the administration of ammonium chloride with radioactive phosphorus as indicator. J. Biol. Chem. 132:219-226, 1940
- P 361 Weissberger, L. H. Phosphorus metabolism in phlorhizin diabetes with radioactive phosphorus as indicator. J. Biol. Chem. 139: 543-550, 1941
- P 362 Weissberger, L. H., Harris, P. H. Effect of tocopherols on phosphorus metabolism. J. Biol. Chem. 151:543-551, 1943
- P 363 Weissberger, L. H., Nasset, E. S. Phosphorus absorption in the anesthetized dog as determined with the radioactive isotope. Am. J. Physiol. 138:149-55, 1942
- P 364 Winkler, A. W., Eisenman, A. J. and Smith, P. K. The use of radioactive isotopes in studies of the permeability of the human erythrocyte. J. of Applied Physics. 12:349, 1941
- P 365 Woodard, H. Q. The relation of tissue phosphatase to the deposition of radioactive phosphorus in bone tumors. J. App. Physics 12:335, 1941
- P 366 Woodard, H. Q. and Higinbotham, N. L. The correlation between serum phosphatase and roentgenographic type in bone disease. Am. J. of Cancer 31:221-237, 1937
- P 367 Woodard, H. Q., Higinbotham, N. L. Serum and tissue phosphatase determinations as an aid in evaluating the radiation therapy of bone tumors. J.A.M.A. 116:1621-1627, 1941
- P 368 Woodard, H. Q., Kenney, J. M. Relation of phosphatase activity in bone tumors to deposition of radioactive phosphorus. Am. J. Roentg. 47:227-239, 1942

- P 369 Wright, V. W. M., The use of radioactive substances in medicine. J. Franklin Institute 234:90-92 1942.
- P 370 Zilversmit, D. B., Entenman, C., Fishler, M. C. The calculation of "turnover time" and "turnover rate" from experiments involving the use of labeling agents. J. Gen. Physiol. 26:325-31 1943.
- P 371 Zilversmit, D. B., Entenman, C., Fishler, M. C., Chaikoff, I. L. The turnover rate of phospholipids in the plasma of the dog as measured with radioactive phosphorus. J. Gen. Physiol. 26:333-40 1943.

#### Addendum

- P 372 Doudoroff, M., Barker, H. A., Hassid, W. Z. Studies with bacterial sucrose phosphorylase as a glucose-transferring enzyme (transglucosidase). J. Biol. Chem. 168:725-32 1947.
- P 373 Hammersten, E., Hevesy, G. Rate of renewal of ribo- and desoxyribonucleic acid. Acta. Physiol. Scand. 11:335-43 1946.
- P 374 Lawrence, J. H. The use of isotopes in medical research. J. Am. Med. Assoc. 134:219-25 1947.
- P 375 Low-Beer, B. V. A. Radioactive phosphorus as an external therapeutic agent in basal cell carcinoma, warts and hemangioma. Am. J. Roentgenol. and Rad. Ther. 58:4-9 1947.
- P 376 Born, H. J., Zimmer, K. G. Anwendung radioaktiver Isotop bei Untersuchungen über die Filtration von Aerosolen. Naturwissenschaften 27:447 1940.



## PLUTONIUM

- Pu 1 Copp, D.H., Axelrod, D.J., Hamilton, J.G. The deposition of radioactive metals in bone as a potential health hazard. Am. J. Roentgenol. and Rad. Ther. 58: 10-16 1947.
- Pu 2 Hamilton, J. G. The metabolism of the fission products and the heaviest elements. Radiol. 49: 325-43 1947.
- Pu 3 Lisco, H., Finkel, M.P., Brues, A.M. Carcinogenic properties of radioactive fission products and of plutonium. Radiol. 58: 361-3 1947.
- Pu 4 Schubert, J. Treatment of plutonium poison metal displacement. Science 105: 389-90 1947.

## POTASSIUM

- K 1 Anderson, E., Joseph, M. Electrolyte excretion studies in rats maintained on low-Na and low-K diets. *Proc. Soc. Exper. Biol. Med.* 40:344-347, 1939.
- K 2 Anderson, E., Joseph, M. Urinary excretion of radioactive Na and K in adrenalectomized rats with and without salt. *Proc. Soc. Exper. Biol. Med.* 40:347-350, 1939.
- K 3 Anderson, E., Joseph, M., Evans, H. M. The use of radio-sodium and radio-potassium in the study of adrenal physiology. *J. Appl. Phys.* 12:316, 1941.
- K 4 Anderson, E., Joseph, M., Herring, V. Changes in excretion of radioactive sodium and potassium and in carbohydrate stores twenty-four hours following adrenalectomy. *Proc. Soc. Exper. Biol. Med.* 42:782-785, 1939.
- K 5 Anderson, E., Joseph, M., Herring, V. Salt after adrenalectomy. II. Urinary excretion of radioactive Na and K in adrenalectomized rats given various levels of salt. *Proc. Soc. Exper. Biol. Med.* 44:482-485, 1940.
- K 6 Anonymous. The exchange of radioactive potassium with body potassium. *Sci. and Culture* 8:304, 1943.
- K 7 Cohn, W. E., and Brues, A. M. Metabolism of tissue cultures. III. A method for measuring the permeability of tissue cells to solutes. *J. Gen. Phys.* 28:449-461, 1945.
- K 8 Cohn, W. M. A note on the quantitative spectrographic analysis of small amounts of rubidium and potassium in biological materials. *J. App. Phys.* 10:200-203, 1939.
- K 9 Colfer, H. F., and Essex, H. E. Radiopotassium autography of the rat's brain. *Proc. Soc. Exp. Biol. Med.* 63:243-244, 1946.



- K 10 Dean, R. B. Anaerobic loss of potassium from frog muscle. J. Cell. and Comp. Physiol. 15:189, 1940.
- K 11 Dean, R. B., Noonan, T. R., Haege, L., Fenn, W. O. Permeability of erythrocytes to radioactive potassium. J. Gen. Physiol. 24: 353-365, 1941
- K 12 Eisenman, A. J., Ott, L., Smith, P. K., Winkler A study of the permeability of the human erythrocytes to potassium, sodium and phosphate by the use of radioactive isotopes. Proc. 34th Ann. Mtg. Am. Soc. Biol. Chem. Mar. 1940.
- K 13 Eisenman, A. J., Smith, P. K., Winkler, A. W., Elkinton, J. R. The transfer of ions across the stomach wall, studied by means of radioactive isotopes. Proc. 35th Ann. Mtg. Am. Soc. Biol. Chem. April, 1941.
- K 14 Eisenman, A. J., Ott, L., Smith, P. K., Winkler, A. W. Study of permeability of human erythrocytes to potassium, sodium, and inorganic phosphate by use of radioactive isotopes. J. Biol. Chem. 135:165-173, 1940.
- K 15 Euler, H., Euler, U. S. and Hevesy, G. The effect of excitation on nerve permeability. Acta Physiologica Scandinavica 12:261-267, 1946.
- K 16 Fenn, W. O. The distribution of radioactive potassium, sodium, and chlorine in rats and rabbits. J. App. Physics 12:316, 1941.
- K 17 Fenn, W. O., Bale, W. F., Mullins, L. J. The radioactivity of potassium from human sources. J. Gen. Physiol. 25:345-353, 1942.
- K 18 Fenn, W. O., Noonan, T. R., Mullins, L. J., Haege, L. F. The exchange of radioactive potassium with body potassium. Am. J. Physiol. 135: 149-163, 1941.
- K 19 Glazko, A. J., Greenberg, D. M. Is physiological activity of potassium due to its natural radioactivity? Am. J. Physiol. 125:405-409, 1939.
- K 20 Greenberg, D. M., Joseph, M., Cohn, W. E., Tufts, E. V. Studies in potassium metabolism of animal body by means of its artificial radioactive isotope. Sci. 87:438, 1938.

- K 21 Hahn, L., and Hevesy, G. Potassium exchange in the stimulated muscle. *Acta Physiologica Scandinavica* 2:51-63, 1941.
- K 22 Hahn, L., and Hevesy, G. Rate of penetration of ions through the capillary wall. *Acta Physiologica Scandinavica* 1:347-361, 1941.
- K 23 Hahn, L. A., Hevesy, G. and Rebbe, O. H. Do the potassium ions inside the muscle cells and blood corpuscles exchange with those present in the plasma? *Biochem. J.* 33:1549-1558, 1939.
- K 24 Hahn, L., Hevesy, G., Rebbe, O. Permeability of corpuscles and muscle cells to potassium ions. *Nature* 143:1021, 1939.
- K 25 Hamilton, J. G. Rates of absorption of radioactive isotopes of sodium, potassium, chlorine, bromine, and iodine in normal human subjects. *Am. J. Physiol.* 124:667-668, 1938.
- K 26 Hamilton, J. G., Alles, G. A. The physiological action of natural and artificial radioactivity. *Am. J. Physiol.* 125:410-413, 1939.
- K 27 Haven, F. L., Hodge, H. C. A review of the applications of radioactive isotopes to the study of growth. *Growth* 5:257-266, 1941.
- K 28 Henderson, W. J., Jones, U. S. The use of radioactive elements for soil and fertilizer studies. *Soil Sci.* 51:283-288, 1941.
- K 29 Hevesy, G. Potassium interchange in the human body. *Acta Physiol. Scand.* 3:123-131, 1942.
- K 30 Hevesy, G. and Hahn, L. Exchange of cellular potassium. *Kgl. Danske Videnskabernes Selskab. Biologiske Meddelelser.* XVI., 1, 1941.
- K 31 Hevesy, G., Hahn, L., Rebbe, O. Circulation of phosphorus in the frog. With a note on the circulation of potassium. *K. Danske Videnskab. Selskab. Biol. Medd.* 16:1-33, 1941.
- K 32 Hevesy, G., Nielsen, N. Potassium interchange in yeast cells. *Acta Phys. Scand.* 2:3-4 347-354, 1941.



- K 33 Hevesy, G. and Zerahn, K. The effect of roentgen rays and ultraviolet radiation on the permeability of yeast. 27:157-158, 1946.
- K 34 Hoagland, D. R., Broyer, T. C., Stout, P. R. Upward movement of salt in the plant with special reference to metabolic activities of roots. Science 91:454, 1940.
- K 35 Katori, S. Über die biologische Wirkung der Radioaktive des Kaliums. Okayama-Igakkai-Zasshi 48:2809-2810, 1936.
- K 36 Katzin, L. I. The ionic permeability of frog skin as determined with the aid of radioactive indicators. The Collecting Net 14: Aug. 12, 1939.
- K 37 Katzin, L. I. The use of radioactive tracers in the determination of irreciprocal permeability of biological membranes. The Collecting Net 15: July 20, 1940.
- K 38 Kimura, Yukichi The effect of potassium on the aerobic glucolysis of brain tissue with reference to the radioactivity of potassium. Sci. Papers Inst. Phys. Chem. Res. (Tokyo) 33:231-245, 1937.
- K 39 Kurnick, N. B. Permeability of human erythrocyte to sodium and potassium. J. Biol. Chem. 140:581-595, 1941.
- K 40 Lark-Horovitz, K. The intake of radioactive sodium and potassium chloride and the testing of enteric coatings. J. App. Physics 12:317, 1941.
- K 41 Lasnitzki, A. On radioactivity of potassium in tumor tissue. Am. J. Cancer 35:225-229, 1939.
- K 42 Lasnitzki, A., Brewer, A. K. An isotopic shift of potassium in human bone-marrow and cancer. Nature, London 149:357, 1942.
- K 43 Lasnitzki, A., Brewer, A. K. The isotopic constitution of potassium in various rat tissues. Biochem. J. 35:144-151, 1941.

- K 44 Levi, H. The action of honey bee-venom on red corpuscles especially on their ionic permeability. *Arkiv. for Kemi, Mineralogi och Geologi* 21A, No. 5, 1945.
- K 45 Levi, H. Note on the permeability of red blood corpuscles to potassium. Kgl. Danske Videnskabernes Selskab Matematisk-Fysiske Meddelelser, 23: Nr. 10, 1945.
- K 46 Lyman, C. P. Penetration of radioactive potassium in denervated muscle. *Am. J. Physiol.* 137:392-395, 1942.
- K 47 Mullins, L. J., Fenn, W. O., Noonan, T. R., Haege, L. F. Permeability of erythrocytes to radioactive potassium. *Am. J. Physiol.* 135: 93-101, 1941.
- K 48 Mullins, L. J., Noonan, T. R., Mullins, L. J., Haege, L. Erythrocyte permeability to radioactive potassium. *Am. J. Physiol.* 133:394, 1941.
- K 49 Nahmias, M. E. The radioactivity of potassium and its influence in karyokinesis. *Cahiers phys.* 17:27-39, 1946.
- K 50 Noonan, T. R., Fenn, W. O., Haege, L. The distribution of injected radioactive potassium in rats. *Am. J. Physiol.* 132:474-488, 1941.
- K 51 Noonan, T. R., Fenn, W. O., Haege, L. The effects of denervation and of stimulation on exchange of radioactive potassium in muscle. *Am. J. Physiol.* 132:612-621, 1941.
- K 52 Pohlmann, J., Gibt es eine Anreicherung des radioaktiven Kaliumisotops in Organismus? *Arch. f. d. ges. Physiol.* 240:377-385, 1938.
- K 53 Pohlmann, J., Netter, H. Enrichment of the radioactive potassium isotope in the organism. *Naturwissenschaften* 26:138, 1938.
- K 54 Stout, P. R. Applications of radioactive K, Rb, Na, P, and Br to studies of the mineral nutrition of higher plants. *J. App. Physics* 12:327, 1941.
- K 55 Stout, P. R., Hoagland, D. R. Upward and lateral movement of salt in



certain plants as indicated by radioactive isotopes of potassium, sodium, and phosphorus absorbed by roots. Am. J. Botany 26:320-324, 1939.

- K 56 Winkler, A. W., Eisenman, A. J. and Smith, P. K. The use of radioactive isotopes in studies of the permeability of the human erythrocyte. J. App. Phys. 12:349, 1941.

#### Addendum

- K 57 Kamen, M. D. Survey of contemporary knowledge of biogeochemistry. I. Isotopic phenomena in biogeochemistry. Bull. Am. Mus. Nat. Hist. 87:105-138, 1946.

## PRASEODYMIUM

- Pr 1      Hamilton, J. G. The metabolism of the fission products  
and the heaviest elements. Radiology 49: 325-43, 1947.



## PROTOACTINIUM

- Pa 1      Hamilton, J. G. The metabolism of the fission products and the heaviest elements. Radiology 49: 325-43, 1947.

## RUBIDIUM

- Rb 1 Greenberg, D.M., Aird, R.E., Boelter, M.D.D., Campbell, W.W., Cohn, W.E., Murayama, M.M. A study with radioactive isotopes of the permeability of blood-cerebrospinal fluid barrier to ions. Am. J. Physiol. 140: 47-64 1943.
- Rb 2 Hamilton, J.G., Alles, G.A. Physiological action of natural and artificial radioactivity. Am. J. Physiol. 125: 410-3 1939.
- Rb 3 Overstreet, R., Jacobson, L. The absorption by roots of rubidium and phosphate ions at extremely small concentration as revealed by experiments with Rb<sup>86</sup> and P<sup>32</sup> prepared without inert carrier. Am. J. Botany 33: 107-12 1946.
- Rb 4 Stout, P.R., Applications of radioactive K, Rb, Na, P, and Br to studies of the mineral nutrition of higher plants. J. App. Phys. 12: 327 1941.



## RUTHENIUM

- Ru 1      Hamilton, J. G. The metabolism of the fission products  
and the heaviest elements. Radiology 49: 325-43, 1947.

## SELENIUM

- Se 1      McConnell, K.P.      Distribution and excretion studies in rat after single subtoxic subcutaneous injection of sodium selenate containing radioselenium. J. Biol. Chem. 141:427-37 1941.
- Se 2      McConnell, K.P.      Respiratory excretion of selenium studied with the radioactive isotope. J. Biol. Chem. 145:55-60 1942.



## SODIUM

- Na 1     Anderson, E., Joseph, M.     Electrolyte excretion studies in rats maintained on low-Na and low-K diets. *Proc. Soc. Exper. Biol. and Med.*    40:344-47    1939.
- Na 2     Anderson, E., Joseph, M.     Urinary excretion of radioactive Na and K in adrenalectomized rats with and without salt. *Proc. Soc. Exper. Biol. and Med.*    40:347-50    1939.
- Na 3     Anderson, E., Joseph, M., Evans, H.M.     The use of radio-sodium and radio-potassium in the study of adrenal physiology. *J. App. Physics* 12:316    1941.
- Na 4     Anderson, Evelyn, Joseph, M., Herring, V.     Changes in excretion of radioactive sodium and potassium and in carbohydrate stores twenty-four hours following adrenalectomy. *Proc. Soc. Exper. Biol. Med.* 42:732-5    1939.
- Na 5     Anderson, E., Joseph, M., Herring, V.     Salt after adrenalectomy. II. Urinary excretion of radioactive Na and K in adrenalectomized rats given various levels of salt. *Proc. Soc. Exper. Biol. and Med.*    44:482-485    1940.
- Na 6     Barany, E.,     Mode of entrance of sodium into the aqueous humor. *Nature* 157:770    1946.
- Na 7     Brewer, A.K., Branley, A.     A radioactive isotope study of the absorption of phosphorus and sodium by corn seedlings. *Science* 91:269-270    1940.
- Na 8     Cohn, W.E., Cohn, E.T.     Permeability of red corpuscles of the dog to sodium ion. *Proc. Soc. Exper. Biol. and Med.*    41:445-9    1939.

- Na 9 Cope, Oliver, Cohn, W.E., Brenizer, A.G., Jr. Gastric secretion II. Absorption of radioactive sodium from pouches of the body and antrum of the stomach of the dog. J. Clin. Invest. 22:103-10 1943.
- Na 10 Cuthbertson, E.M. and Greenberg, D.M. Chemical and pathological changes in dietary chloride deficiency in the rat. J. of Biol. Chem. 160:83-94 1945.
- Na 11 Donnelly, G.L., Ross, C.J., Meroney, W.H., Holman, R.L. Studies on heavy metal poisoning: II. Sodium citrate therapy effective 67 hours after uranium injury. Proc. Soc. for Exper. Biol. and Med. 57:75-78 1944.
- Na 12 Eisenman, A.J., Smith, P.K., Winkler, A.W., Elkinton, J.R. The transfer of ions across the stomach wall, studied by means of radioactive isotopes. Proc. 35th Ann. Mtg. Am. Soc. Biol. Chem. April, 1941.
- Na 13 Eisenman, A.J., Ott, L., et al A study of the permeability of the human erythrocytes to potassium, sodium and phosphate by the use of radioactive isotopes. Proc. 34th Ann. Mtg. Am. Soc. Biol. Chem. March, 1940.
- Na 14 Eisenman, A.J., Ott, L., Smith, P.K., Winkler, A.W. A study of the permeability of human erythrocytes to potassium, sodium, and inorganic phosphate by the use of radioactive isotopes. J. Biol. Chem. 135:No.1 1940.
- Na 15 Eisenman, A.J., Smith, P.K., Winkler, A.W., Elkinton, J.R. The transfer of ions across the stomach wall, studied by means of radioactive isotopes. Proc. of the 35th Ann. Mtg. of Amer. Soc. Biol. Chem. April 15-19, 1941.



- Na 16 Euler, H., Euler, U.S., Hevesy, G. The effect of excitation on nerve permeability. *Acta Physiologica Scandinavica* Vol. 12 Fasc. 2-3 1946.
- Na 17 Evans, T.C., Quimby, E.H. Studies on the effects of radioactive sodium and of roentgen rays on normal and leukemic mice. *Am. J. Roent. and Radium Therapy.* 55:55-56.- 1946.
- Na 18 Fenn, W.O. The distribution of radioactive potassium, sodium, and chlorine in rats and rabbits. *J. App. Physics.* 12:316 1941.
- Na 19 Flexner, L.B., Gellhorn, A. The comparative physiology of placental transfer. *Am. J. Obst. and Gynec.* 43:965-74 1942.
- Na 20 Flexner, L.B., Gellhorn, A. The transfer of water and sodium to the amniotic fluid of the guinea pig. *Am. J. Physiol.* 136:757-61 1942.
- Na 21 Flexner, L.B., Pohl, H.A. Transfer of radioactive sodium across the placenta of the cat. *Proc. Soc. Exper. Biol. and Med.* 44: 345-6 1940.
- Na 22 Flexner, L.B., Pohl, H.A. Transfer of radioactive sodium across placenta of guinea pig. *Am. J. Physiol.* 132:594-606 1941.
- Na 23 Flexner, L.B., Pohl, H.A. The transfer of radioactive sodium across the placenta of the rabbit. *Am. J. Physiol.* 134:344-9 1941.
- Na 24 Flexner, L.B., Pohl, H.A. The transfer of radioactive sodium across the placenta of the white rat. *J. Cell. and Comp. Physiol.* 18:49-59 1941.
- Na 25 Flexner, L.B., Roberts, R.B. Measurement of placental permeability with radioactive sodium; the relation of placental permeability to fetal size in the rat. *Am. J. Physiol.* 128:154-8 1939.

- Na 26 Fox, Charles, L., Jr. Oral sodium lactate in the treatment of burn shock. J. M. Am. Med. Assoc. 124:207-12; 1922-44
- Na 27 Fox, C.L., Keston, A.S. The mechanism of shock from burns and trauma traced with radiosodium. Surgery, Gynecol., Obstet. 80:561-7 1945.
- Na 28 Gellhorn, A., Flexner, L.B. Transfer of water across the placenta of the guinea pig. Am. J. Physiol. 136: No.5 1942.
- Na 29 Gellhorn, A., Flexner, L.B., Hellman, L.M. A transfer of sodium across the human placenta. Am. J. Obs. and Gyn. 46:668-672 1943.
- Na 30 Gellhorn, A., Flexner, L.B., Pohl, H.A. The transfer of radioactive sodium across the placenta of the sow. J. Cell. and Comp. Physiol. 18:393-400 1941.
- Na 31 Gellhorn, A., Merrell, M., Rankin, R.M. The rate of transcapillary exchange of sodium in normal and shocked dogs. Am. J. Physiol. 142:407-27 1944.
- Na 32 Greenberg, D.M., Campbell, W.W., Murayama, M. Studies in mineral metabolism with the aid of artificial radioactive isotopes: V. absorption, excretion and distribution of labeled sodium in rats maintained on normal and low sodium diets. J. Biol. Chem. 136:35-46 1940.
- Na 33 Greenberg, D.M., Aird, R.B., Baelter, M.D.D., Campbell, W.W., Cohn, W.E., Murayama, M.M. A study with radioactive isotopes of the permeability of blood-cerebrospinal fluid barrier to ions. Am. J. Physiol. 140:47-64 1944.
- Na 34 Griffiths, J.H.E., Maegraith, B.G. Distribution of radioactive sodium after injection into rabbit. Nature, London 143:159-60 1939.



- Na 35 Hahn, L., Hevesy, G. Rate of penetration of ions through the capillary wall. *Acta Physiologica Scandinavica* Vol. 1. Fasc 4 347-361 1941.
- Na 36 Hahn, L.A., Hevesy, G., Rebbe, O.H. Do the potassium ions inside the muscle cells and blood corpuscles exchange with those present in the plasma? *Biochem. J.* Vol. 33:1549 1939.
- Na 37 Hamilton, J.G. The rates of absorption of radioactive isotopes of sodium, potassium, chlorine, bormine, and iodine in normal human subjects. *Am. J. Physiol.* 124:667-8 1939.
- Na 38 Hamilton, J.G. The rates of absorption of radiosodium in normal human subjects. *Proc. Natl. Acad. Sci.* 23:521-7 1937.
- Na 39 Hamilton, J.G., Alles, G.A. The physiological action of natural and artificial radioactivity. *Am. J. Physiol.* 125:410-3 1939.
- Na 40 Hamilton, J.G., Stone, R.S. Excretion of radiosodium following intravenous administration in man. *Proc. Soc. Exper. Biol. and Med.* 35:595-8 1937.
- Na 41 Hamilton, J.G., Stone, R.S. The intravenous and intraduodenal administration of radiosodium. *Radiology* 28:178-88 1937.
- Na 42 Hammarsten, E., Hevesy, G. Rate of renewal of ribo and desoxyribo nucleic Acids. *Acta Physiologica Scandinavica* Vol. 11:335-343 1946.
- Na 43 Haven, F.L., Hodge, H.C. A review of the applications of radioactive isotopes to the study of growth. *Growth* 5:257-66 1941.
- Na 44 Heppel, L.A. The diffusion of radioactive sodium into the muscles of potassium-deprived rats. *Am. J. Physiol.* 128:449-54 1940.
- Na 45 Hoagland, D.R., Broyer, T.C. Accumulation of salt and permeability in plant cells. *J. Gen. Physiol.* 24:865 1942.

- Na 46 Hoagland, D.R., Broyer, T.C., Stout, P.R. Upward movement of salt in the plant with special reference to metabolic activities of roots. Science 91:454 1940.
- Na 47 Hodge, H.C., Koss, W.F., Ginn, J.T., Falkenheim, M., Gavett, E., Fowler, R.C., Thomas, I., Bonner, J.F., and Dessauer, G., The nature of the insoluble sodium of bone. The absorption of sodium at forty degrees by bone, dentin, enamel, and hydroxyapatite as shown by the radioactive isotope. J. Biol. Chem. 148:321-331 1943.
- Na 48 Hubbard, J.P., Preston, W.N., Ross, R.A. Velocity of blood flow in infants and young children determined by radioactive sodium. J. Clin. Inv. 21:613-7 1942.
- Na 49 Johnston, G.W., Lee, C.O. A radioactive method of testing absorption from ointment bases. J. of Amer. Pharm. Assoc. 32:278-280 1943.
- Na 50 Jorgensen, C.B., Levi, H., Ussing, H.H. On the influence of the neurohypophyseal principles on the sodium metabolism in the axolotl (Ambystoma mexicanum) Acta Physiologica Scandinavica 12:350-371 1946.
- Na 51 Kaltreider, N.L., Meneely, G.R., Allen, J.R., Bale, W.F. Determination of the volume of the extracellular fluid of the body with radioactive sodium. J. Exper. Med. 74:569-90 1941.
- Na 52 Katzin, L.I. The ionic permeability of frog skin as determined with the aid of radioactive indicators. The Collecting Net 14:No 6, August 12, 1939.
- Na 53 Katzin, L.I. The use of radioactive tracers in the determination of irreciprocal permeability of biological membranes. The Collecting Net. XV July 20, 1940.



- Na 54 Kinsey, V.E. and others Sodium, chloride and phosphorus movement and the eye. Archives of Ophthalmology 27:1126-1131 1942.
- Na 55 Koss, W.F., Ginn, J.T. Distribution of sodium in teeth and bones of dogs as shown by radioactive isotope. J. Dent. Res. 20:465-70 1941.
- Na 56 Kurnick, N.B. Permeability of human erythrocyte to sodium and potassium. J. Biol. Chem. 140:581-95 1941.
- Na 57 Lark-Horovitz, K. The intake of radioactive sodium and potassium chloride and the testing of enteric coatings. J. App. Physics 12:317 1941.
- Na 58 Lindgren, E. Versuche mit radioaktiven Isotopen bei Leukämiebehandlung. Acta Radiol. 25:614-24, 1944.
- Na 59 Manery, J.F., Bale, W.F. The penetration of radioactive sodium and phosphorus into the extra-and intra-cellular phases of tissues. Am. J. Physiol. 132:215-31 1941.
- Na 60 Medes, G., Floyd, N.F., Weinhouse, S. Fatty acid metabolism. IV. Ketone bodies as intermediates of acetate oxidation in animal tissues. J. Biol. Chem. 162:1-9, 1946.
- Na 61 Merrell, M., Gellhorn, A., Flexner, L.B. Studies on rates of exchange of substances between the blood and extra-vascular fluid; II. The exchange of sodium in the guinea pig. J. Biol. Chem. 153:83-9 1944.
- Na 62 Montgomery, M.L., Sheline, C.E., Chaikoff, I.L. Elimination of sodium in pancreatic juice as measured by radioactive sodium. Am. J. Physiol. 131:578-83, 1941.
- Na 63 Myers, W.G. Some applications of atomic energy to diagnosis and therapy. Ohio J. Sci. 46(4):197-199, 1946.

- Na 64 Nathanson, I.T., Nutt, A.L., Pope, A., Zamecnik, P.C., Aub, J.C.,  
Brues, A.M., Kety, S.S. The toxic factors in experimental traumatic shock I. Physiologic effects of muscle ligation in the dog. *J. of Clin. Invest.* 24:829-34 1945.
- Na 65 Pohl, H.A., Flexner, L.B. Transfer of radioactive sodium across the placenta of the cat. *J. Biol. Chem.* 139:163-73, 1941.
- Na 66 Pohl, H.A., Flexner, L.B., Gellhorn, A. The transfer of radioactive sodium across the placenta of the goat. *Am. J. Physiol.* 134:338-43, 1941.
- Na 67 Pommerenke, W.T., Hahn, P.F. Absorption of radioactive sodium instilled into the vagina. *Am. J. Obst. and Gyn.* 46:853-55, 1943.
- Na 68 Pommerenke, W.T., Hahan, P.F. Secretion of radioactive sodium in human milk. *Proc. Soc. Exptl. Biol. Med.* 52:223-4 1943.
- Na 69 Popp, W.C., Binger, M.W. The use of pentobarbital sodium for Rontgen nausea and vomiting. *Radiology* 28:211-13, 1937.
- Na 70 Quimby, E.H. Radioactive sodium as a tool in medical research. Manuscript.
- Na 71 Quimby, E.H., Smith, B.C. Tracer studies with radioactive sodium in patients with peripheral vascular disease. *Science* 100:175-7, 1944.
- Na 72 Reaser, P.B., Burch, George. Radiosodium tracer studies in congestive heart failure. *Proc. Soc. Exp. Biol. and Med.* 63(3):543-546, 1946.
- Na 73 Shibuya, R., Takenouchi, T. Studies on the radioactive sodium chloride. III. On the treatment of lymphadenitis tuberculosa by the active salt. II. *Tokyoer Med. Wochenschr.* 3169:69-80, 1940.



- Na 74 Smith, B.C., Quimby, E.H. The use of radioactive Na in studies of circulation in patients with peripheral vascular disease. Surg. Gyn., Obstet. 79:142-7, 1944.
- Na 75 Smith, Beverly C., Quimby, Edith H. The use of radioactive sodium as a tracer in the study of peripheral vascular disease. Radiology 45:335-46, 1945.
- Na 76 Sohrne, G. Diagnostic use of radioactive common salt. Acta. Radiol. 26:279-284, 1945.
- Na 77 Stout, P.R. Applications of radioactive K, Rb, Na, P, and Br, to studies of the mineral nutrition of higher plants. J. App. Physics 12:327, 1941.
- Na 78 Stout, P.R., Hoagland, D.R. Upward and lateral movement of salt in certain plants as indicated by radioactive isotopes of potassium, sodium, and phosphorus absorbed by roots. Am. J. Botany 26:320-4, 1939.
- Na 79 Thompson, S.A., Quimby, E.H., Smith, B.C. The effect of pulmonary resuscitative procedures upon the circulation as demonstrated by the use of radioactive sodium. Surgery, Gynecology and Obstetrics, Sept. 1946, Vol. 83, 387-391.
- Na 80 Thygesen, J.E., Videbaek, A., Villaume, I. Treatment of leukemia with artificial radioactive sodium; preliminary report. Acta. Radiol. 25:305-16, 1944.
- Na 81 Visscher, M.B., Fetcher, E.S., Jr., Carr, C.W., Gregor, H.P., Bushey, M.S., Barker, D.E. Isotopic tracer studies on the movement of water and ions between intestinal lumen and blood. Am. J. Physiol. 142:550-75, 1944.

- Na 82 Vißscher, M.B., Varco, R.H., Carr, C.W., Dean, R.B, Erickson, D.  
Sodium ion movement between the intestinal lumen and the blood.  
Am. J. Physiol. 141:488-505, 1944.
- Na 83 Visscher, M.B., Carr, C.W. The rate of entrance of Rd-Na into  
the aqueous humor and cerebrospinal fluid. Am. J. Physiol.  
142:27-31, 1944.
- Na 84 Winkler, A.W., Eisenman, A.J., Smith, P.K. The use of radioactive  
isotopes in studies of the permeability of the human erythrocyte.  
J. of Applied Physics 12:349, 1941.
- Na 85 Winkler, A.W., Elkinton, J.R., Eisenman, A.J. Comparison of sul-  
focyanate with radioactive chloride and sodium in measurement of ex-  
tracellular fluid. Am. J. Physiol. 139:239-246, 1943.



## STRONTIUM

- Sr 1 Copp, D. H., Greenberg, D. M. Studies on bone fracture healing. I. Effect of Vitamins A and D. J. Nutrition 29: 261-67, 1945.
- Sr 2 Erf, L. A., Pecher, C. Secretion of radio-strontium in milk of two cows following intravenous administration. Proc. Soc. Exper. Biol. and Med. 45: 762-2, 1940.
- Sr 3 Greenberg, D. M. Studies in mineral metabolism with the aid of artificial radioactive isotopes. VIII. Tracer experiments with radioactive calcium and strontium on the mechanism of Vitamin D action in rachitic rats. J. Biol. Chem. 157: 99-104, 1945.
- Sr 4 Greenberg, D. M., Aird, R. B., Baelter, M.D.D., Campbell, W.W., Cohn, W.E., Murayama, M. M. A study with radioactive isotopes of the permeability of blood-cerebrospinal fluid barrier to ions. Am. J. Physiol. 140: 47-64, 1944.
- Sr 5 Greenberg, D. M., Troescher, F. M. Study with radioactive isotopes of excretion of calcium and strontium by way of bile. Proc. Soc. Exper. Biol. and Med. 49: 488-91, 1942.
- Sr 6 Hamilton, J. G. The use of radioactive tracers in biology and medicine. Radiology 39: 541-72, 1942.
- Sr 7 Hodge, H. C. Gavett, E., Thomas, I. The absorption of strontium at forty degrees by enamel, dentin, bone, and hydroxyapatite as shown by the radioactive isotope. J. Biol. Chem. 163: 1-6, April 1946.
- Sr 8 Lawrence, J. H. Observations on the nature and treatment of leukemia and allied diseases (Edwin R. Kretschmer Memorial lecture) Proc. Inst. Med. Chicago 14: 30-49, 1942.

- Sr 9 Low-Beer, B.V.A., Lawrence, J.H., Stone, R.S. The therapeutic use of artificially produced radioactive substances; radiophosphorus, radio-strontium, radio-iodine, with special reference to leukemia and allied diseases. *Radiology* 39: 573-97, 1942.
- Sr 10 Marx, W., Reinhardt, W. O. Lack of effect of growth hormone on deposition of radiostrontium in bone. *Proc. Soc. Exper. Biol. and Med.* 51: 112-114, 1942.
- Sr 11 Pecher, C. Biological investigations with radioactive calcium and strontium. *Proc. Soc. Exper. Biol. and Med.* 46: 86-90, 1941.
- Sr 12 Pecher, C. Biological investigations with radioactive calcium and radioactive strontium. Simultaneous production of a radiostrontium for therapeutic bone irradiation and a radio-yttrium suitable for metallic radiography. *J. App. Physics* 12: 318, 1941.
- Sr 13 Pecher, C. Biological investigations with radioactive calcium and strontium; preliminary report on the use of radioactive strontium in the treatment of metastatic bone cancer. *Univ. Calif. Publ. Pharmacol.* 2: 117-49, 1943.
- Sr 14 Pecher, C., Pecher, J. Radiocalcium and radiostrontium metabolism in pregnant mice. *Proc. Soc. Exper. Biol. and Med.* 46: 910-4, 1941.
- Sr 15 Treadwell, A. deG., Low-Beer, B.V.A., Friedell, H.L., Lawrence, J.H. Metabolic studies on neoplasm of bone with the aid of radioactive strontium. *Am. J. Med. Sci.* 204: 521-30, 1943.
- Sr 16 Tweedy, W. R. The effect of parathyroid extract upon the distribution, retention, and the excretion of labeled strontium. *J. Biol. Chem.* 161: 105-13, 1945.
- Sr 17 Weissberger, L.H., Harris, P.L. A possible vitamin D assay technique with radioactive strontium. *J. Biol. Chem.* 144: 287-8, 1942.



- Sr 18 Wright, V. W. M. The use of radioactive substances in medicine.  
J. Franklin Inst. 234:90, 1942.

Addendum

- Sr 19 Lisco, H., Finkel, M. P., Brues, A. M. Carcinogenic properties of  
radioactive fission products and of plutonium. Radio. 58:361-363,  
1947.

# SULFUR

- S 1    Aten, Jr., A. H. W., Hevesy, G.    Fate of the sulphate radical in the animal body. *Nature* 142:952, 1938.
- S 2    Borsook, H., Buchman, E. R., Hatcher, J. B., Yost, D. M., McMillan, E.    The course of thiamine metabolism in man as indicated by the use of radioactive sulfur. *Proc. Natl. Acad. Sci. U. S.* 26:412-418, 1940.
- S 3    Borsook, H., Hatcher, J. B., Yost, D. M.    The course of vitamin B<sub>1</sub> (thiamin) metabolism in man as indicated by the use of radioactive sulfur. *J. App. Physics* 12:325, 1941.
- S 4    Borsook, H., Keighley, G., Yost, D. M., McMillan, E.    The urinary excretion of ingested radioactive sulfur. *Science* 86:525, 1937.
- S 5    Committee on Growth    Symposium on the use of isotopes in biological research. March 3 and 4, 1947 (mimeographed).
- S 6    Dziewiatkowski, D. D.    Fate of ingested sulfide sulfur labeled with radioactive sulfur in the rat. *J. Biol. Chem.* 161:723-729, 1945.
- S 7    Dziewiatkowski, D. D.    Conversion of sulfide sulfur to cystine sulfur in the rat with use of radioactive sulfur. *J. Biol. Chem.* 164:165, 1946
- S 8    Franklin, R. G.    The preparation of glutathione containing radioactive sulfur. *Science* 89:298-300, 1939.
- S 9    Franklin, R. G.    The preparation of glutathione containing radioactive sulfur. *J. Franklin Inst.* 227:No. 5, 722-727, 1939.
- S 10    Hamilton, J. G., Axelrod, D.    Determination of the distribution of H and L in skin and eye tissues by radio-autographic techniques, progress report. OSRD Report 1911.



- S 11 Harrison, B. F., Thomas, M. D., Hill, G. R. Radioautographs showing the distribution of sulfur in wheat. *Plant Physiol.* 19:245-257, 1944.
- S 12 Melchior, J. B., Tarver, H. Studies in protein synthesis in vitro I. On the synthesis of labeled cystine ( $S^{35}$ ) and its attempted use as a tool in the study of protein synthesis. *Arch. of Biochem.* 12:301-307, 1947.
- S 13 Melchior, J., Tarver, H. Studies on protein synthesis in vitro II. On the uptake of labeled sulfur by the proteins of liver slices incubated with labeled methionine ( $S^{35}$ ). *Arch. of Biochem.* 12:309-315, 1947.
- S 14 Sacks, J. Effect of insulin on phosphate turnover in muscle. *Univ. Hosp. Bull. Ann Arbor* 9:87-88, 1943.
- S 15 Schoenheimer, R. The dynamic state of body constituents. pp. 25-65 (Cambridge, Mass.) 1942.
- S 16 Seligman, A. M., Fine, J. Traumatic shock. I. The production of radioactive plasma protein from amino acids containing radioactive sulphur. *J. Clin. Invest.* 22:265-273, 1943.
- S 17 Seligman, A. M., Rutenburg, A. M., Banks, H. Traumatic shock II. The preparation of cystine, methionine, and homocystine containing radioactive sulphur. *J. Clin. Invest.* 22:275-9, 1943.
- S 18 Singher, H. O., Marinelli, L. Distribution of radioactive S in the rat. *Science* 101:414-415, 1945.
- S 19 Smythe, C. V., Halliday, D. An enzymic conversion of radioactive sulfide sulphur to cystine sulphur. *J. Biol. Chem.* 144:237-242, 1942.
- S 20 Tarver, H. Studies on sulphur metabolism with special reference to the conversion of methionine to cystine. Thesis. Univ. of Calif. Graduate Div.

- S 21 Tarver, H., Reinhardt, W. O. Methionine labeled with radioactive sulphur as an indicator of protein formation in the hepatectomized dog. J. Biol. Chem. 167:395-400, 1947.
- S 22 Tarver, H., Schmidt, C. L. A. Conversion of methionine to cystine; experiments with radioactive sulphur ( $S^{35}$ ). J. Biol. Chem. 130: 67-80, 1939. (Prelim. Report Proc. Soc. Exper. Biol. and Med. 41: 442-443, 1939.)
- S 23 Tarver, H., Schmidt, C. L. A. The use of radioactive sulphur,  $S^{35}$ , for metabolic studies. J. App. Physics 12:323, 1941.
- S 24 Tarver, H., Schmidt, C. L. A. Radioactive sulphur studies. Synthesis of methionine. Conversion of methionine sulphur to taurine sulphur in dogs and rats. Distribution of sulphur in the proteins of animals fed sulphur or methionine. Experiments in vitro with sulphur and hydrogen sulfide. J. Biol. Chem. 6:69-84, 1942.
- S 25 Tarver, H., Schmidt, C. L. A. The urinary sulphur partition in normal and cystinuric dogs fed labeled methionine. J. Biol. Chem. 167:387-394, 1947.
- S 26 Thomas, M. D., Hendricks, H., Hill, G. R. Some chemical reactions of sulphur dioxide after absorption by alfalfa and sugar beets. Plant Physiol. 19:212-226, 1944.
- S 27 Thomas, M. D., Hendricks, R. H., Bryner, L. C., Hill, G. R. A study of the sulphur metabolism of wheat, barley; and corn using radioactive sulphur. Plant Physiol. 19:227-244, 1944.
- S 28 Thomas, M. D., Hendricks, R. H., Hill, G. R. Apparent equilibrium between photosynthesis and respiration in an unrenewed atmosphere. Plant Physiol. 19:270-376, 1944.
- S 29 Harrison, B. F., Thomas, M. D., Hill, G. R. Radioautographs showing the distribution of sulphur in wheat. Plant Physiol. 19:245-257, 1944.



- S 30 Tuck, J. L. Radioactive sulphur for biochemical experiments. J. Chem. Soc. 1939:1292-1294, 1939.
- S 31 duVigneaud, V., Kilmer, G. W., Rachele, J. R., Cohn, M. On the mechanism of the conversion in vivo of methionine to cystine. J. Biol. Chem. 155:645-651, 1944.

## TELLURIUM

- Te 1 De Meio, R.H., Henrique, F.C., Jr. Tellurium IV. Excretion and distribution in tissues studied with a radioactive isotope. J. Biol. Chem. 159: 609-23 1947.
- Te 2 Hamilton, J.G. The metabolism of the fission products and the heaviest elements. Radiol. 49: 325-43 1947.



## TRITIUM

- T 1 Committee on Growth Symposium on the use of isotopes in biological research. March 3 and 4, 1947.
- T 2 Norris, T.H., Ruben, S., Allen, M.B. Tracer studies with radioactive hydrogen. Some experiments on photosynthesis and chlorophyll. J. Am. Chem. Soc. 64: 3037-40 1942.
- T 3 Pace, N., Kline, L., Schachman, H.K., Harfenist, M. Studies on body composition. IV. Use of radioactive hydrogen for measurement in vivo of total body water. J. Biol. Chem. 168: 459-69 1947.

## XENON

- Xe 1 Hamilton, J. G., The metabolism of the fission products and the heaviest elements. Radiol. 49: 325-43 1947.
- Xe 3 Jones, H., Dobson, E., Lawrence, J. Tracer studies of blood-tissue perfusion rates at rest and a new criterion of blood mixing times. Abst. Comm., XVII Internat. Physiol. Cong., pp. 28-9 1947.
- Xe 3 Lawrence, J. H., Loomis, W.F., Tobias, C.A., Turpin, F.H. Preliminary observations on the narcotic effect of xenon with a review of values for solubilities of gases in water and oils. J. Physiol. 105: 197-207 1946.



## YTTRIUM

- Y 1 Copp, D.H., Axelrod, D.J., Hamilton, J.G. The deposition of radioactive metals in bone as a potential health hazard. Am. J. Roentgenol. and Rad. Ther. 58: 10-16 1947.
- Y 2 Dobson, E., Kelly, L., Jones, H., Gofman, J. Radioactive substances specifically localized in liver, spleen, or bone marrow. Abst. Comm., XVII Internat. Physiol. Cong., pp. 26-7 1947.
- Y 3 Hamilton, J. G. The metabolism of the fission products and the heaviest elements. Radiol. 49: 325-43 1947.
- Y 4 Lisco, H., Finkel, M.F., Brues, A.M. Carcinogenic properties of radioactive fission products and of plutonium. Radiol. 58: 361-3 1947.

## ZINC

- Zn 1 Montgomery, M. L., Sheline, G.E., Chaikoff, I. L. The elimination of administered zinc in pancreatic juice, duodenal juice and bile of the dog as measured by its radioactive isotope (Zn 65). J. Exper. Med. 78: 151-9 1943.
- Zn 2 Sheline, G.E. Studies on the metabolism of zinc with the aid of its radioactive isotope (Zn 65). Thesis, Univ. of Calif. Graduate Div., 1943.
- Zn 3 Sheline, G.E., Chaikoff, I.L., Jones, H.B., Montgomery, M.L. Studies on the metabolism of zinc with the aid of its radioactive isotope II. (The distribution of administered radioactive zinc in the tissues of mice and dogs). J. Biol. Chem. 149: 139-51 1943.
- Zn 4 Sheline, G.E., Chaikoff, I.L., Jones, H.B., Montgomery, M.L. Studies on the metabolism of zinc with the aid of its radioactive isotope. I. The excretion of administered zinc in urine and feces. J. Biol. Chem. 147: 409-14 1943.



## ZIRCONIUM

- Zr 1 Copp, D.H., Axelrod, D.J, Hamilton, J.G. The deposition of radioactive metals in bone as a potential health hazard. *Am. J. Roentgenol. and Rad. Ther.* 58: 10-16 1947.
- Zr 2 Dobson, E., Kelly, L., Jones, H., Gofman, J. Radioactive substances specifically localized in liver, spleen, or bone marrow. *Abst. Comm., XVII Internat. Physiol. Cong.*, pp. 26-7 1947.
- Zr 3 Hamilton, J. G. The metabolism of the fission products and the heaviest elements. *Radiol.* 49: 325-43 1947.
- Zr 4 Lisco, H., Finkel, M. P., Brues, A.M. Carcinogenic properties of radioactive fission products and of plutonium. *Radiol.* 58: 361-3 1947.

1. Stable Isotopes . . . . .	39
2. Stable Isotope Spins, Magnetic Moments, and Quadrupole Moments .	51
3. Average Energy of Beta Particles . . . . .	113
4. Average Ionization Potentials . . . . .	125
5. Atomic Stopping Power for Alpha Particles Relative to Air at NTP.	128
6. Ranges of RaC Alpha Particles in Various Substances. . . . .	131
7. Secondary Electrons Produced by Alpha Particles in Tissue . . .	141
8. Secondary Electrons Produced by Protons in Tissue. . . . .	153
9. Scattering Lengths for Slow Neutrons . . . . .	206
9a. Thermal Neutron Activation Cross Sections . . . . .	211
10. Atomic Mass and Spin of Radioisotopes . . . . .	259
11. Radioactive Isotopes. . . . .	262
12. Alpha Particles from the Natural Radioactive Series . . . . .	351
13. "Neptunium" Series . . . . .	364
14. Fission Yields . . . . .	388
15. Fusible Compounds Used for Cyclotron Targets . . . . .	424
16. Ionization Potentials of Counter Gases. . . . .	440
17. Disintegration Rates of the Naturally Occuring Uranium Isotopes.	476
18. Radiations from RaD, RaE, and Po . . . . .	479
19. Ionization by Gamma Sources of Different Energy. . . . .	481
20. Source Strength of Various Isotopes . . . . .	482
21. Geometrical Efficiency and Obliquity Factor for a Point Beta Particle Source . . . . .	485
22. Relative Efficiency of Disc to Point Source . . . . .	486



## TABLES

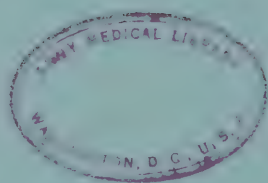
Page Page

23. Inorganic Composition of Human Blood . . . . .	537
24. Inorganic Composition of Man . . . . .	538
25. Important and Stable Isotopes That Have Been Used in Biological and Medical Investigations . . . . .	599
26. Potentially Valuable Tracer Isotopes, Especially Those of Elements for Which Biological Tracer Studies Have Not Yet Been Carried Out . . . . .	606
27. Isotopes Used in Radiotherapy and Clinical Diagnosis . . .	660





**HANDBOOK OF RADIOACTIVITY AND TRACER  
METHODOLOGY**



**UNITED STATES AIR FORCE  
AIR MATERIEL COMMAND  
Wright-Patterson Air Force Base  
Dayton, Ohio**

### **NOTE**

When drawings, specifications, and other data prepared by the War Department are furnished to manufacturers and others for use in the manufacture or purchase of supplies, or for any other purpose, the Government assumes no responsibility nor obligation whatever; and the furnishing of said data by the War Department is not to be regarded by implication or otherwise, or in any manner licensing the holder, or conveying any rights or permission to manufacture, use, or sell any patented inventions that may in any way be related thereto.

---

The information furnished herewith is made available for study upon the understanding that the Government's proprietary interests in and relating thereto shall not be impaired. It is desired that the Patent & Royalties Section, Office of the Judge Advocate, Air Materiel Command, Wright Field, Dayton, Ohio, be promptly notified of any apparent conflict between the Government's proprietary interests and those of others.

---

### **Espionage Act**

**Notice:** This document contains information affecting the national defense of the United States within the meaning the Espionage Act (U. S. C. 50:31, 32). The transmission of this document or the revelation of its contents in any manner to an unauthorized person is prohibited by law. (AR 380-5, paragraph 17 b.)

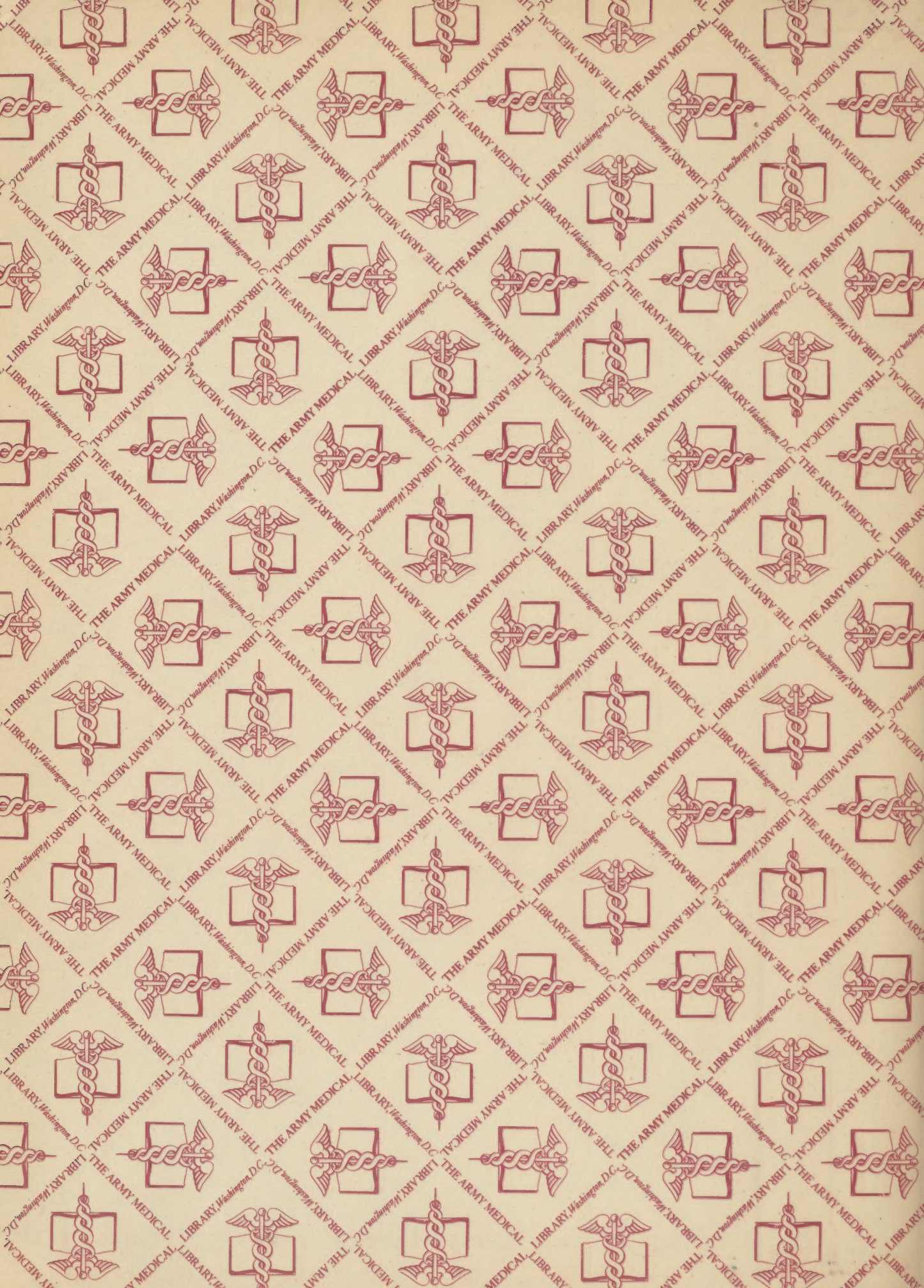
"The above Espionage Notice can be disregarded unless this document is plainly marked with a security classification as "Restricted," "Confidential," "Secret," or "Top Secret."

---

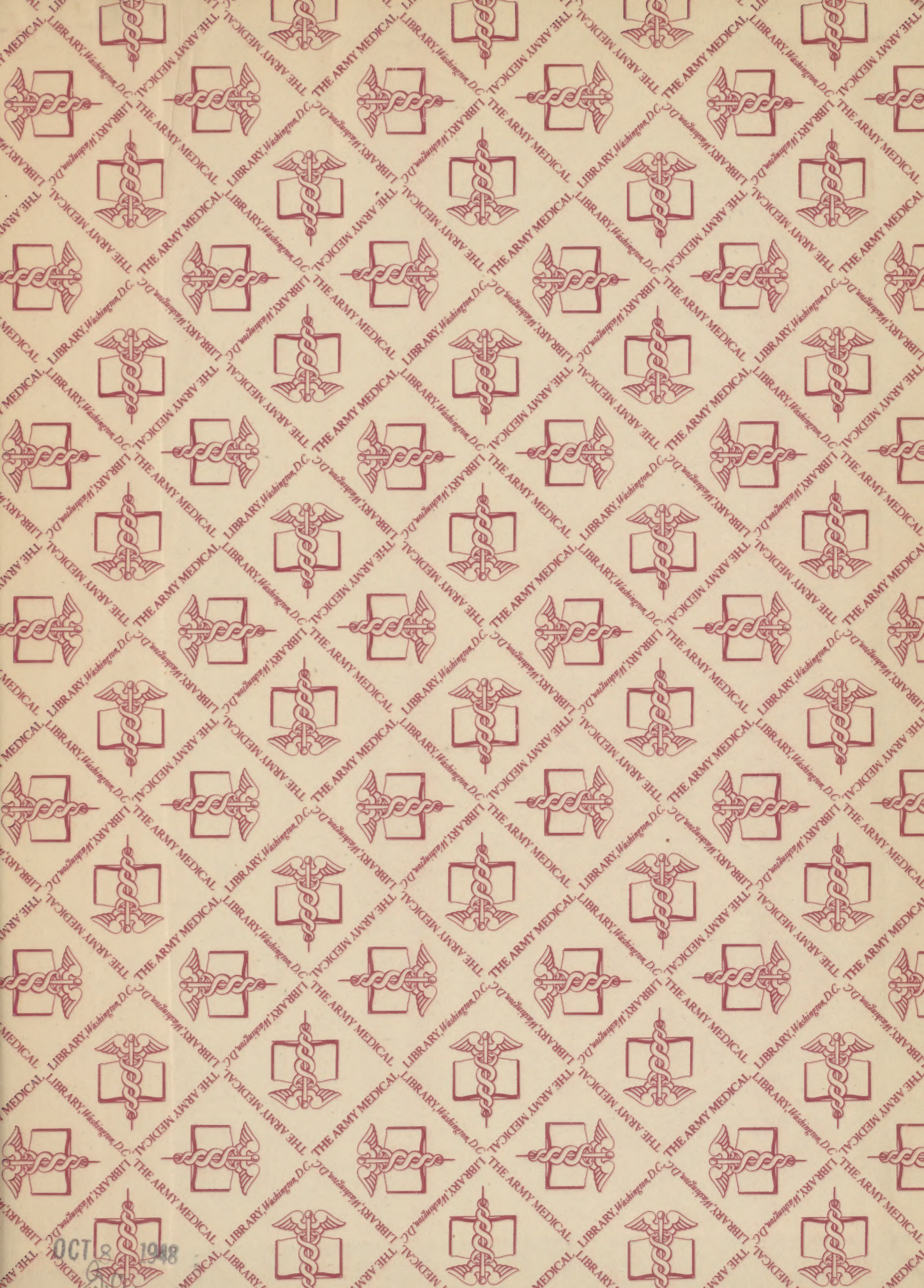
The U. S. Government is absolved from any litigation which may ensue from the contractor's infringing on the foreign patent rights which may be involved.











OCT 8 1948  
100



NATIONAL LIBRARY OF MEDICINE



NLM 02155977 1